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## BULLETIN VIII

# AN INVESTIGATION OF THE PROBLEM OF GUIDING DOWNSTREAM-MIGRANT SALMON AT DAMS

BY

F. J. ANDREW, L. R. KERSEY and P. C. JOHNSON

PARTICIPATING ORGANIZATIONS

INTERNATIONAL PACIFIC SALMON FISHERIES COMMISSION
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NEW WESTMINSTER, B. C.
CANADA
1955

INTERNATIONAL PACIFIC SALMON
FISHERIES COMMISSION

APPOINTED UNDER A CONVENTION
BETWEEN CANADA AND THE UNITED STATES FOR THE
PROTECTION, PRESERVATION AND EXTENSION OF
THE SOCKEYE SALMON FISHERIES IN
THE FRASER RIVER SYSTEM

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## ABSTRACT

Experiments were conducted in Sweltzer Creek at Cultus Lake on the Fraser River watershed in 1953 and 1954 and at Baker Dam on Baker River in the State of Washington in 1955 to determine the practicability of using artificial stimuli to guide downstream-migrant sockeye salmon. Profound problems encountered in prototype experiments eliminate, at present, the possibility that artificial stimuli can be used as an effective and practical method for protecting downstream-migrant salmon at dams. A unique type of electrical screen—the "galvanotropic screen"—was developed which was over 90 per cent effective in previous small-scale experiments but it was not effective in large-scale experiments at Baker Dam. Other artificial stimuli—air bubbles, light, shade, and visible barriers—were found to produce some directional effect but they were much less effective than galvanotropic stimuli in the small-scale experiments.

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# AN INVESTIGATION OF THE PROBLEM OF GUIDING DOWNSTREAM-MIGRANT SALMON AT DAMS

## INTRODUCTION

The salmon populations of the Fraser River system have long been recognized as a resource of great economic value. In 1937, following a serious decline in the Fraser River sockeye salmon population *(Oncorhynchus nerka)*, the governments of the United States and Canada created the International Pacific Salmon Fisheries Commission to protect, preserve, and extend the sockeye salmon fishery of the Fraser River system. Scientific investigations carried out by this Commission disclosed that the principal cause of the decline was an obstruction at Hell's Gate which blocked the passage of upstream-migrant salmon at certain water levels. This blockade was eliminated by the construction of fishways in 1945. Removal of this and other obstructions, rehabilitation of depleted areas, and scientific regulation of the commercial fishery have resulted in a substantial increase in the production of Fraser River sockeye. The total catch for the four-year period from 1951 to 1954 was 18,246,000 sockeye compared with 6,478,000 sockeye taken in the previous brood years of 1947 to 1950. The current wholesale value of the *increase* in the pack for the last four years is $42,192,000 (International Pacific Salmon Fisheries Commission, Annual Report for 1954). Through the application of scientific management procedures the commercial catch can continue to increase.

However, as a result of the increasing demand for hydroelectric power in British Columbia, this valuable salmon resource is again threatened. Available information indicates that the many dams proposed for construction on the Fraser River watershed could practically eliminate the Fraser River salmon resource. Despite the elaborate and costly facilities that have been provided for the upstream passage of adult salmon at hydroelectric dams on the Columbia River, the production of salmon decreased markedly after the dams were built. The production of adult sockeye from the Baker River has declined 55 per cent since construction of the Baker River Dam in 1925 (Hamilton and Andrew, 1954). In compliance with that term of reference which states that the International Pacific Salmon Fisheries Commission is required *to protect* the Fraser River sockeye salmon fishery, a program of research was instituted in 1950 to study some of the problems that would have to be solved before hydroelectric dams could be constructed on the Fraser River watershed without serious damage to the fisheries resource.

*One* of the many important problems that would be introduced by the construction of a dam on a sockeye salmon migration route is the provision of safe downstream passage past the dam for one-year-old fish in their journey from the lake rearing area to the ocean. At this stage of their life the fish are usually about three to four inches in length and are referred to as yearlings, downstream migrants, or smolts. They possess a strong urge to move downstream and are easily drawn into hydroelectric, irrigation or other intakes. Experiments conducted at Baker Dam in 1951 and 1952 showed that over 95 per cent of the downstream-migrant sockeye migrated from the reservoir over the surface spillway

where they suffered a mortality of 64 per cent (Hamilton and Andrew, 1954). Studies reported by Schoeneman and Junge (1954) also confirm that excessive rates of mortality are incurred by downstream-migrant salmon at dams. Available information indicates that the survival rate in the ocean does not increase to compensate for mortalities incurred during the seaward migration (Hamilton and Andrew, 1954).

Although there are no known methods for eliminating these excessive mortalities to downstream-migrant salmon at large hydroelectric dams, certain possibilities have been suggested. Fine-mesh wire screens can be used to prevent fish from entering small diversion channels but for a large intake, such as the spillway of a dam, wire screens have been considered impractical because of their initial cost and the subsequent operating problems. It has also been suggested that spillways and turbines might be designed so that mortalities to downstream migrants would be reduced but this involves a great many practical and presently unsolved problems. Another possibility is that various artificial stimuli might be used in the forebay of a dam to repel fish from hazardous areas and to attract them to a safe by-pass.

The primary aim of the investigation described in this report was to study as many artificial stimuli as possible and to determine the practicability of using one or more of them for protecting the migration of sockeye at dams. Although laboratory experiments were used in some instances to obtain preliminary information, the various guiding methods were evaluated in field experiments conducted with native sockeye.

There are three main sections in this report. The first describes an experiment conducted at Cultus Lake in 1953 to compare the effects of various stimuli. In 1954 a similar experiment was conducted in which a more comprehensive investigation of electrical stimuli was made. This investigation is described in the second section. The final section describes a prototype experiment conducted at Baker Dam in 1955.

## RELATIVE GUIDING EFFICIENCIES OF VARIOUS STIMULI

The aim of the initial field experiment, conducted in the spring of 1953, was to perform tests with as many separate artificial stimuli as possible in order to determine which of these stimuli would be most promising for further investigation. It was considered important that the experiments be conducted with native downstream-migrant sockeye in their natural environment as hatchery-reared fish or native fish that had been retained under artificial conditions for a period of time might become conditioned to various stimuli or might not possess the strong urge to migrate downstream. The experiments were therefore conducted in a stream with a native run of downstream-migrant sockeye.

The experimental site was located in Sweltzer Creek about 1000 feet downstream from the outlet of Cultus Lake on the Fraser River watershed. Installations at the site, shown in Figures 1 and 2, consisted of a test area, 24 feet wide and 30 feet long, with a 130-foot-long wire screen fence built across the stream at the

upstream end to lead the fish into the test area, and a plank dam built across the stream at the downstream end to maintain a water depth of 3 feet in the test area. The sides of the test area, built of plywood, extended from the stream bed to about one foot above the water surface. The bottom consisted of stream gravel up to three inches in diameter. The water was very clear and its velocity was maintained at about 0.25 feet per second.

Fish entered the test area through a four-foot-wide gate in the center of the upstream end. At the downstream end they could move out of the test area through two four-foot openings, one on either side. From the compartments immediately downstream from these openings they were carried by the water velocity into inclined-plane traps from which they could not escape. The entrance to each trap was a horizontal slot 4 feet long and 3 inches wide submerged 1 foot below the water surface. Most of the water, after discharging through these slots, dropped through sloping wire screens located between the slots and the trap enclosures and the remainder swept the fish into the trap enclosures.

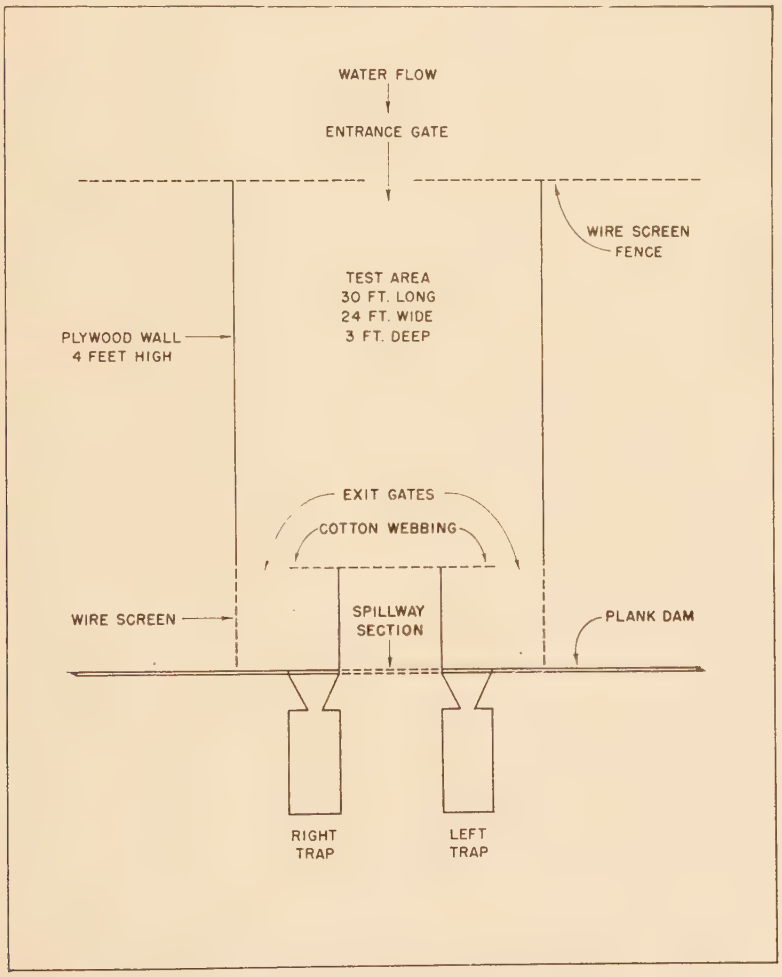


FIGURE 1. Plan view of test area used for experiments in Sweltzer Creek, 1953.

During the period of the experiment, from April 10 to May 7, about 450,000 downstream-migrant sockeye moved through the test area. The size of these fish varied little during the period of the experiment. The range in length was from 2.86 to 4.60 inches. On April 13, 239 migrants were measured and the fork length (from tip of the snout to fork of the caudal fin) averaged 3.64 inches. The average fork length of 306 fish measured on May 5 was 3.68 inches.

The tests were conducted in the following manner. A stimulus to be tested was applied in front of either the left or right exit gate at the downstream end of the test area. The entrance gate at the upstream end of the test area was then opened to admit fish that were migrating downstream. All observers stayed clear of the test area until sufficient time had elapsed for a large number of fish to

FIGURE 2. Experimental site used for the guiding experiments in Sweltzer Creek in 1953.

accumulate in the traps, then the trap entrances were blocked with pieces of wire screen, the gate at the upstream end of the test area was closed, and the stimulus was discontinued. The fish caught in each trap were removed and counted. Control runs (no stimulus applied) were also conducted using the same procedure. These control runs, which were conducted periodically throughout the entire experimental period, were used to determine the proportion of fish that would be expected in each trap if no stimulus were applied.

In tests where the trap catches were small the fish were counted individually but usually the number of fish was so great that this would have been too time-consuming. A volumetric method of counting was therefore adopted whereby fish were removed from the traps by dip nets and placed in a perforated-metal

cylinder 6 inches in diameter and 10 inches deep. When enough fish had been added to fill the cylinder to a certain level, they were returned to the stream and the cylinder was refilled. The cylinder was frequently calibrated.

In order to evaluate the effectiveness of a particular stimulus in attracting or repelling the fish, the distribution of fish between the two traps resulting from the application of this stimulus was compared with the distribution occurring when no stimulus was applied. The best measure of the guiding efficiency was obtained by relating the number of fish guided to the number of fish available for guiding. Then

Percentage efficiency of guiding

$$= \frac{(\text{Number of fish attracted or repelled from one of the traps}) \times 100}{\text{Number of fish available for guiding}}$$

$$= \frac{(\text{Observed catch in trap behind stimulus—Expected catch in this trap}) \times 100}{\text{Expected catch in trap from which the fish were guided away}}$$

Positive guiding efficiencies indicate that the fish were attracted by the stimulus and negative efficiencies indicate that the fish were repelled.

Twenty-four control runs were conducted throughout the experimental period to measure the expected distribution between the two traps under experimental conditions comparable to those existing when applied stimuli were being tested. It was found that there was a significant preference for the trap on the right side of the test area. These controls involved a total of 96,500 fish, of which 61.86 per cent entered the trap on the right side. A 95 per cent confidence interval of $\pm$ 6.86 per cent was calculated by means of the formula $u = \bar{x} \pm \frac{St}{\sqrt{n}}$

where $\bar{x}$ = mean percentage in right trap

$n$ = number of observations

$S^2$ = variance

$t$ = Student's "t" (5 per cent confidence point for n-1 degrees of freedom)

A detailed statistical analysis of the results was deemed unnecessary since the object of the experiment was to isolate those stimuli that guided almost all the fish. Furthermore, variations in the control distributions were relatively unimportant because a stimulus could be considered practical only when it consistently guided nearly all the fish to one of the exits. A stimulus to be tested was usually applied first on one side of the test area then on the other but where it was inconvenient to alternate in this manner, the stimulus was applied on the side of the test area where most of the fish were expected.

### Rising Air Bubbles

The use of an air bubble barrier for guiding downstream-migrant sockeye was suggested by the work of other experimenters. Janssen (1938) described the use of streams of air bubbles to keep schools of fish from sounding while being brailed out of a net and to keep sharks away from tuna impounded in a purse seine.

Bramsnaes, *et al* (1945) described laboratory experiments in which certain species of fish could not be forced through a veil of air bubbles rising from the bottom of a tank.

Veils of rising air bubbles were produced in the test area in Sweltzer Creek by passing air into the water through holes in two iron pipes laid on the stream bottom. The pipes were 2 inches in diameter and 20 feet long with 1/16-inch diameter holes spaced 2 inches apart in a single row. Each pipe extended from the center of the downstream wall of the test area to a plywood side wall and formed an angle of 37° with the direction of water flow. A veil of rising air bubbles could therefore be produced on either side of the test area. Standard rubber air hose was used to connect each pipe to a gas-driven air compressor

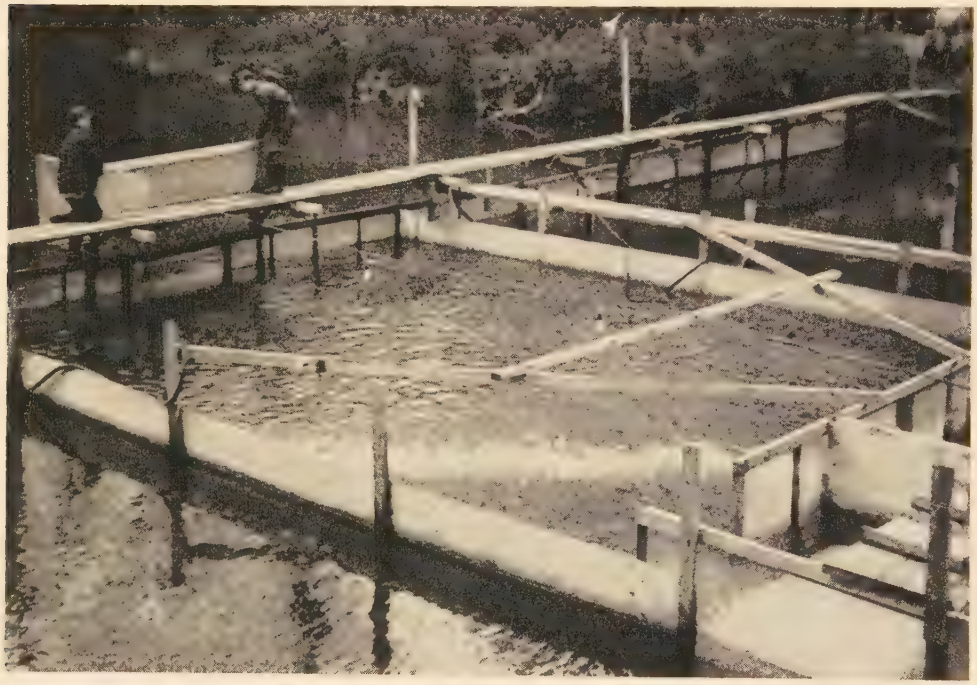

FIGURE 3. Surface turbulence produced by rising air bubbles.

situated on the stream bank. This compressor was rated at 35 horsepower and was designed to deliver 105 cubic feet of air per minute. Figure 3 shows the surface turbulence produced by the rising air bubbles.

The data presented in Table 1 show the results of all experiments with veils of air. During periods of daylight the fish appeared to be attracted to the side where the air bubbles were produced. Although an average guiding efficiency of 25.9 per cent was obtained during daylight, the extreme variability from 1 per cent to 88 per cent indicated that air bubbles alone during periods of daylight would be of little or no value for practical application. The efficiencies were also very low during periods of darkness when no artificial illumination was used. In these two tests the fish showed a tendency to be repelled by the air bubble wall. The four

TABLE 1

EFFICIENCIES OF GUIDING WITH A VEIL OF AIR BUBBLES

| Date | Time Start | Time End | Total Fish | Guiding Efficiency (Per cent) Attraction | Guiding Efficiency (Per cent) Repulsion |
|---|---|---|---|---|---|
| 1953 | | *Daylight Tests* | | | |
| April | | | | | |
| 16 | 3:45 p.m. | 5:30 p.m. | 578 | 88.0 | |
| 16 | 7:25 p.m. | 7:35 p.m. | 11,261 | 1.6 | |
| 17 | 2:05 p.m. | 2:23 p.m. | 9,387 | 41.1 | |
| 17 | 2:47 p.m. | 3:25 p.m. | 6,197 | 1.4 | |
| 17 | 3:45 p.m. | 4:18 p.m. | 7,119 | 3.7 | |
| 18 | 1:37 p.m. | 1:55 p.m. | 13,438 | 33.6 | |
| 18 | 2:55 p.m. | 3:15 p.m. | 17,393 | 2.3 | |
| 18 | 4:36 p.m. | 5:01 p.m. | 13,986 | 55.0 | |
| 19 | 3:04 p.m. | 3:10 p.m. | 7,969 | 14.6 | |
| 19 | 4:08 p.m. | 4:14 p.m. | 8,027 | 3.6 | |
| | | Average efficiency | | 25.9 | |
| | | *Darkness Tests* | | | |
| 16 | 8:06 p.m. | 9:45 p.m. | 481 | | 23.7 |
| 17 | 8:13 p.m. | 9:25 p.m. | 347 | | 11.0 |
| | | Average efficiency | | | 18.4 |
| | | *Darkness Tests with Air Bubbles Illuminated* | | | |
| 60-watt bulb 30 inches above the water surface in the center of the test area, upstream from bubbles. | | | | | |
| 13 | 8:00 p.m. | 8:15 p.m. | 3,668 | | 88.0 |
| 15 | 8:00 p.m. | 8:20 p.m. | 3,256 | | 45.3 |
| 15 | 8:40 p.m. | 9:00 p.m. | 7,484 | | 95.0 |
| 16 | 9:55 p.m. | 11:00 p.m. | 404 | | 29.2 |
| | | Average efficiency | | | 74.2 |
| 3—10-watt bulbs suspended at mid-depth, 2 ft. behind bubbles. | | | | | |
| 18 | 7:09 p.m. | 7:19 p.m. | 23,726 | | 16.3 |
| 3—10-watt bulbs, 1 ft. above surface, 2 ft. behind bubbles. | | | | | |
| 18 | 8:06 p.m. | 8:21 p.m. | 14,226 | | 68.1 |

tests that were conducted with a 60-watt incandescent bulb suspended 30 inches above the water surface in the center of the test area, 7 feet upstream from the end of the air pipe, indicated that the efficiency was increased when the veil of air bubbles was illuminated. In these tests 74.2 per cent of the fish were repelled from the trap in front of which the wall of bubbles was produced. Experiments were then conducted using three 10-watt lights in order to obtain a more uniform light distribution. These lights were placed 24 inches downstream from and parallel to the wall of air bubbles. There was no apparent change in the guiding efficiency when the lights were placed one foot above the water surface but the guiding efficiency was considerably lower when they were submerged 18 inches below the water surface.

It seems that during daylight the surface turbulence produced by rising bubbles afforded some protection for the fish but that during darkness the fish did not seek the protection of surface turbulence and were therefore repelled by the rising bubbles. The myriad reflections from the moving bubbles and turbulent water surface may have frightened the fish away when the air bubbles were illuminated at night. Veils of rising air bubbles might therefore be used during daylight to create turbulent protected areas in by-passes for downstream-migrant sockeye. By-passes might be made more attractive in this way but the low guiding efficiencies obtained in these experiments indicated that a veil of air bubbles would not be effective if used alone to guide downstream-migrant sockeye away from a hazardous area.

### Lights

Artificial light has been used on many occasions in attempts to affect the movement of fish. Lights have been used successfully in the commercial fisheries of several countries for attracting fish into nets. Fry (1950) and McKernan (1940) reported that certain species of downstream-migrant salmon were attracted to lights. Fields and Finger (1954) and Brett, *et al* (1954) have shown that fingerling salmon can be repelled by lights.

The experiments at Cultus Lake in which lights were used in attempts to guide sockeye were limited in number because only on a few occasions did the migration occur during periods of darkness. In four tests lights were suspended about 2 feet above the water surface and 6 feet upstream from one of the trap entrances, with their beams directed downward. A shade was used to maintain

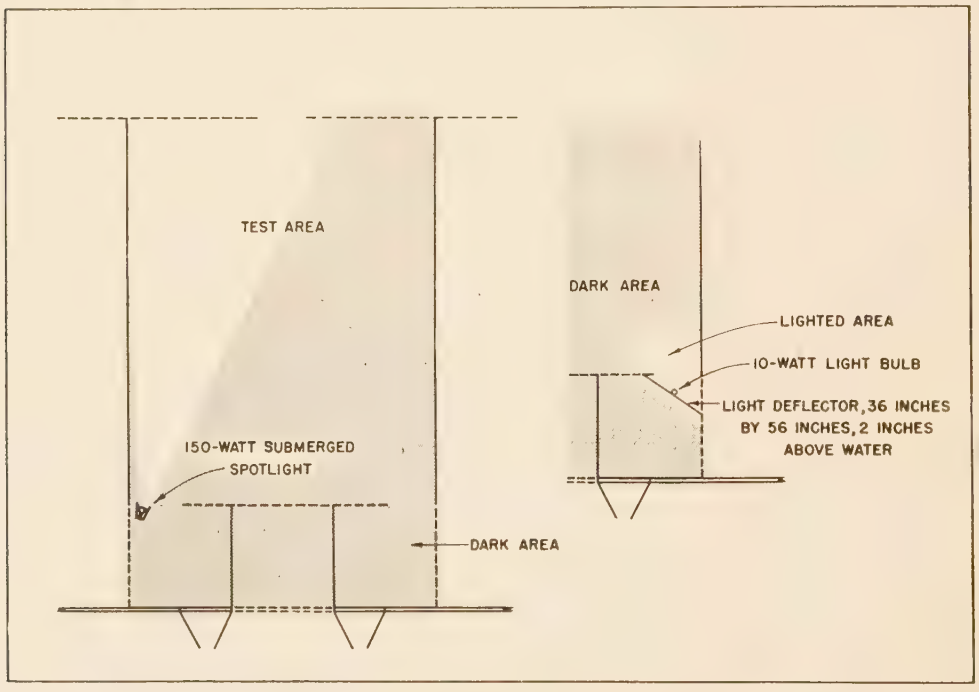


FIGURE 4. Position of lights in test area.

a dark area at the trap entrance. In three other tests, 150-watt submerged spotlights were placed at mid-depth 6 feet upstream from the trap entrances, as shown in Figure 4. Table 2 summarizes the results of these two groups of tests.

TABLE 2

EFFICIENCIES OF GUIDING WITH LIGHTS

| Date | Time Start | Time End | Total Fish | Guiding Efficiency (Per cent) Attraction | Guiding Efficiency (Per cent) Repulsion | Remarks |
|---|---|---|---|---|---|---|
| 1953 April | | | | | | |
| 10 | 8:00 p.m. | 9:00 p.m. | 829 | | 2.7 | 100-watt surface light |
| 10 | 9:05 p.m. | 10:00 p.m. | 452 | 45.6 | | 100-watt surface light |
| 19 | 7:50 p.m. | 10:00 p.m. | 116 | | 61.6 | 10-watt surface light |
| 24 | 9:32 p.m. | 10:25 p.m. | 4,897 | 30.3 | | 10-watt surface light |
| Average efficiency using surface lights upstream from trap entrance, directed downward. | | | | 25.5 | | |
| 23 | 7:37 p.m. | 7:51 p.m. | 4,274 | 49.1 | | 150-watt subsurface spotlight |
| 24 | 8:13 p.m. | 8:22 p.m. | 9,615 | 37.9 | | 150-watt subsurface spotlight |
| 24 | 8:58 p.m. | 9:10 p.m. | 6,700 | 97.6 | | 150-watt subsurface spotlight |
| Average efficiency using 150-watt subsurface spotlight at trap entrance, directed upstream | | | | 59.6 | | |

The results in tests with surface lights were inconsistent. Fish were attracted to the lighted side in two tests and repelled in the other two tests. A 100-watt incandescent lamp did not appear to have any more effect than a 10-watt lamp. Results obtained with the submerged spotlight were more consistent, however. The fish were attracted to the lighted side in all three tests, the average efficiency being 59.6 per cent.

When submerged spotlights were used, the fish swam into the beam of light and proceeded along the beam to the lamp. At this point they congregated and gradually drifted downstream into the dark area at the trap entrance, where they were swept by the water velocity into the trap enclosure. During these experiments fish could be seen in the brightly illuminated beam immediately upstream from the spotlight but no fish congregated upstream from the unlit spotlight on the other side of the test area. When one light was turned off and the other turned on fish moved almost immediately into the newly lighted area.

Further evidence was obtained in these experiments to indicate that yearling sockeye were attracted to light. Occasionally, during darkness, after the daily migration had ceased, two 100-watt floodlights were turned on along the walkway which paralleled the wire screen fence. These lights faced upstream and were directed downward, producing a 6-foot diameter circle of bright light on the stream bottom in the 3-foot deep clear water. When the lights were first turned

on, no fish were present in the lighted areas but within a very short time small numbers of fingerling sockeye could be seen swimming from relatively dark areas toward the lighted areas. When these fish reached the circle of light, they remained there for several minutes. When the floodlight was very slowly rotated so that the circle of light moved across the stream, the fish usually followed the lighted area.

It is conceivable that fish are attracted to lighted areas as a result of their schooling behavior: when a few fish become visible in lighted areas other fish join them. With lights that produce diffused illumination over a large area, however, it seems reasonable that fish would be repelled because they have the natural tendency to seek protection. It is suggested therefore that when the light illuminates a small area within a large dark area, the fish will have a tendency to be attracted whereas if the entire passageway is illuminated the fish will either evade the lighted area or will obtain an orientation with respect to the sides or bottom and will not be so readily carried downstream by the current.

Although light appears to be partially effective as a guiding method, its practical use would be very limited since many fish migrate through turbid water and also during periods of daylight. Migration probably occurs both at night and during the day in fast rivers such as the Fraser and Thompson. The relatively low guiding efficiencies obtained in the field experiments at Cultus Lake indicate that the use of lights shows little promise at present as a method of guiding downstream-migrant sockeye at large-scale installations.

### Shade

Observations made from time to time during the downstream migration of yearling sockeye salmon in various rivers have indicated that yearling sockeye often follow along shaded passageways. This was apparent in the forebay of Baker Dam (Hamilton and Andrew, 1954) and in the test area in Sweltzer Creek. It therefore appeared that shade might be used to guide downstream-migrant sockeye.

To obtain a measure of the guiding efficiency that might be achieved with this method, a 6-foot wide shaded area was created along the left wall of the test area, extending from the entrance gate at the upstream end to the entrance of the trap on the left side. The shaded or protective area was produced by floating a number of panels covered with black tar paper on the water surface. During the period of these tests the sky was overcast and although a significant attraction to the shaded side was observed, higher guiding efficiencies might have been achieved during periods of bright sunlight. The results of the three tests that were conducted are given in Table 3. It can be seen that the guiding efficiencies were consistent and that an average of 58.0 per cent of the fish available for guiding were attracted to the shaded side. Although it is unlikely that shade could be used to guide fish effectively in the deep turbid waters upstream from large dams, these results show that a shaded or protective passageway might be used as an aid in guiding downstream-migrant sockeye during daylight hours.

TABLE 3

EFFICIENCIES OF GUIDING WITH SHADE

| Date | Time | | Total Fish | Guiding Efficiency (Per cent) |
|---|---|---|---|---|
| | Start | End | | |
| 1953 | | | | Attraction |
| April | | | | |
| 20 | 3:59 p.m. | 4:05 p.m. | 18,533 | 59.2 |
| | 4:32 p.m. | 4:42 p.m. | 17,472 | 56.8 |
| | 5:05 p.m. | 5:13 p.m. | 5,143 | 57.6 |
| | | | Average efficiency | 58.0 |

## Electricity

On many occasions in the past, attempts have been made to use electrical stimuli to screen fingerlings out of irrigation canals and various other water intakes but apparently all attempts with migrating salmon have failed. Holmes (1948), in a history of the development of electric fish screens, showed that electric screens have been studied in the United States since 1917. It appears, however, that in all these attempts electric screens were designed to scare fish back upstream or to one side of the stream. More recently, experiments have been conducted in an effort to utilize the fact that many species of fish can be forced by unidirectional electrical stimuli to orient themselves and swim to a positive electrode. Since orientative electrical stimuli appeared to be the most promising for controlling or directing the movement of downstream-migrant salmon, these stimuli have been studied more thoroughly than other electrical stimuli in this investigation. These studies involved three phases: a search of the available literature, laboratory experiments to study the response of yearling sockeye to unidirectional electrical stimuli, and small-scale field experiments in the test area at Cultus Lake.

A search of the literature revealed that the study of the reaction of fish to electricity dates back to at least 1863 when Isham Baggs, an Englishman, was granted a patent for a fishing device which consisted of two parallel plates connected to a battery. Fish swimming between these plates would become paralyzed and would therefore be easily captured. Since that time a vast number of experiments have been conducted in various countries to study the reactions of fish to electrical currents.

Hermann (1885) observed that when small animals were placed in a direct current field, they oriented themselves so that their heads faced the anode. This reaction was termed "galvanotropism". A second reaction of actively swimming toward the anode was termed "galvanotaxis". These reactions were confirmed by several other experimenters before the turn of the century. Scheminsky (1924) observed an additional reaction that he called "oscillotaxis": the fish tended to orient themselves so as to be parallel to the electrodes and thus perpendicular to the lines of current flow. The fact that the fish would experience a minimum voltage drop across its body when in this position (and therefore a minimum of

discomfort) could explain this orientation but the reason for the galvanotropic reaction is not so apparent. Early experimenters believed that direct current stimulated certain nerve cells which forced the fish to react by orienting to the anode. Other experimenters felt that certain nerves stimulated by direct current received a minimum of stimulation when the head of the fish was directed toward the anode. Van Harreveld (1938) showed galvanotropism to be a reflex reaction resulting from stimulation of sensory end-organs in the muscles. Nicolai (1930) appears to be the first to study the effect of different types of electrical current on galvanotropism and he showed that a galvanotropic response could be produced by interrupted direct current. Morgan (1953) suggested that interrupted direct current was more desirable than continuous current because of the increased galvanotactic response and also because of the appreciable reduction in electrical energy consumption.

Other applications have been made in various parts of the world. Smolian (1944) recommended the use of direct current for catching fish in streams for obtaining samples of the resident population, population estimates, or for ridding streams of undesirable species. A number of applications using direct current have been made in the United States and in Canada in connection with the management of sport-fish populations; Rayner (1949) reported that good success had been achieved with both continuous and interrupted direct current. European experiments have shown that electricity might be used in commercial fishing to collect fish from large bodies of water such as lakes or the ocean. Groody, *et al* (1952) demonstrated that Pacific sardines *(Sardinops caerulea)* could be led very successfully to the positive electrode in an experimental trough containing salt water when unidirectional current pulses were used. It was therefore concluded that it might be possible to use an electrical field upstream from a dam to attract downstream-migrant sockeye into a by-pass channel where safe downstream passage past the dam would be ensured.

To investigate this possibility laboratory experiments were conducted to determine whether yearling sockeye would exhibit a galvanotropic response and if so, what electrical characteristics would be required. In preliminary tests conducted at the University of British Columbia observations were made of the reaction of hatchery-reared yearling sockeye to different electrical stimuli. Many combinations of voltage gradient, pulse duration and pulse frequency were studied using direct current, interrupted direct current, condenser discharges and gradually rising direct current pulses. The fish exhibited galvanotropism when exposed to certain electrical stimuli, especially interrupted direct current. Interrupted direct current pulses of long duration produced a more pronounced galvanotropic response than those of short duration. Duty cycles from 75 to 95 per cent (percentage of time that the current flowed during each cycle) and pulse frequencies from 4 to 7 pulses per second appeared to be the most effective. Condenser discharges of relatively short duration caused the fish to be more active than usual but did not produce galvanotropism. The voltage gradient required for producing galvanotropism was higher for small than for large fish. The fish used in these experiments were only slightly smaller than native Cultus Lake sockeye migrants. Galvanotropism was not definite when the conductivity of the water was low but

became more definite as the conductivity was increased. The fish were immobilized after a few seconds of exposure to the intensity of current that was required for producing the galvanotropic response.

In the first series of field experiments with electricity at Cultus Lake an attempt was made to utilize the demonstrated tendency of fish to swim towards a positive electrode. It was expected that when a direct current field was produced across a stream, the fish would move towards the positive electrode and would pass downstream in the sheltered area behind this electrode, from which they could be led into a by-pass. Electrodes were therefore arranged in two rows, one on each side of the 24-foot wide test area (Figure 5). Each row consisted of 13 vertical pieces of 1-inch diameter galvanized pipe, spaced 2 feet apart in each row, with a distance of 20 feet between the two rows. This provided a 2-foot space between the plywood walls and the rows of electrodes. The pipe electrodes were supported vertically by wooden stakes driven into the gravel bottom of

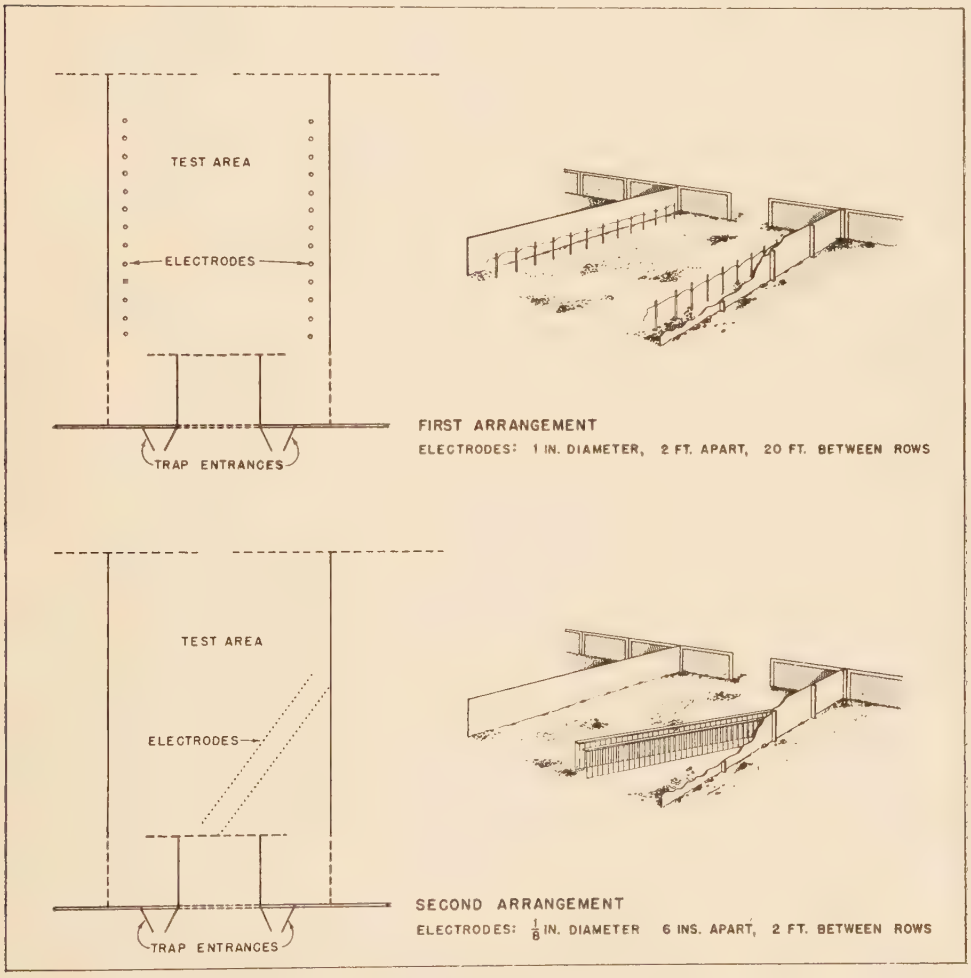


FIGURE 5. Arrangement of electrodes in test area.

the test area. The pipes extended from the water surface to about 3 inches above the stream bed.

From the results of the previous laboratory studies it appeared that the best galvanotactic response would be obtained by energizing the electrodes with either interrupted direct current or gradually rising direct current pulses. Since there was no convenient and economical method for producing gradually rising direct current pulses of the magnitude required for the field experiments, interrupted direct current was used. The apparatus consisted of a compound-wound direct-current generator connected to the electrodes through a rotating switch. This switch consisted of three circular 5-inch diameter bakelite discs rotated on a single shaft by a small shunt-wound direct-current motor. One half of the circumference of each of the two outer discs and the entire circumference of the center disc were covered with continuous copper strips. Each disc and its attached copper strip was one-quarter of an inch wide. Spring-mounted carbon brushes made contact with the circumference of each disc. By changing the relative positions of the conducting surfaces of the outer discs and the wiring connections between the discs it was possible to permit current to flow for any desired fraction of a shaft revolution. The frequency of interruption of the current flow was controlled by adjusting the speed of the small driving motor.

In the initial experiments interrupted direct current was used at a frequency of 4 pulses per second and a duty cycle of 75 per cent. However, instead of being attracted to the positive row of electrodes, the fish remained schooled in the area between the two electrode rows and did not move downstream out of the test area. When a peak intensity of 160 volts was used, the thousands of fish that entered the test area remained in a large school extending to within 12 inches of the cathode row and to within 18 inches of the anode row. The fish tended to maintain a position at right angles to the lines of current flow and to crowd towards the cathode side. When the polarity was changed the fish gradually moved towards the new cathode. Those that accidentally approached too close to the cathode (less than 12 inches) exhibited pronounced distress but were usually able to escape from the localized fields near these electrodes. Those that entered too close to the anode were attracted with such pronounced force that they hit an anode electrode and then circled it until they became immobilized or killed. When the voltage was increased to 300, the school moved into a smaller area between the electrodes, extending again as close as 12 inches from the cathode row but not coming closer than 48 inches from the anode row; otherwise their reaction was the same as at 160 volts except that more fish were killed when they ventured too close to an electrode. Field-strength measurements showed that the voltage gradient was very high near the electrodes but, since the current flowed through a large expanse of water and gravel, it rapidly diminished to a low value a short distance away from the electrodes. Burrowing of fish into the gravel near the cathodes demonstrated that there was an appreciable flow of current through the gravel.

Attraction of fish to a positive electrode, although possible in an insulated laboratory tank, was not possible in these experiments because the voltage gradient

between the electrode rows could not be made uniform. It was therefore concluded that guiding downstream-migrant sockeye at large-scale installations by using galvanotropic stimuli to attract them over considerable distances would be infeasible.

Although this experiment was in itself a failure, three concepts were evolved from it which led to the design of a special electric screen. The first concept was that in order to prevent fish from being immobilized and killed, it would be necessary to use a uniform field, thus eliminating unduly high voltage gradients at the electrodes. Second, since the fish with very few exceptions remained beyond a certain minimum distance from the electrodes, they might stay upstream from and be guided by an electrical field that extended in a narrow band across one of the trap entrances. Third, if this narrow electrified band were arranged so that the upstream side of the electrified zone was positively charged, any fish that entered the electrified zone might be forced to swim upstream to the positive electrode. Accordingly a special array of electrodes was constructed. It was 20 feet long and consisted of two parallel rows spaced 24 inches apart, each row being made of vertical pieces of ⅛-inch galvanized iron wire spaced 6 inches apart. This array was suspended with one end placed at the center of the downstream end of the test area and the other end placed adjacent to the plywood wall on the left side. When in this position the two rows formed an angle of approximately 37° with the direction of stream flow and each vertical wire extended from the water surface to the stream bed. Figure 5 shows the construction and position of this electrode arrangement.

When the electrodes were energized with a galvanotropic stimulus with the upstream row positive, excellent guiding efficiences were achieved. As the fish approached the upstream row of electrodes the electric field became progressively more intense; many fish were therefore induced to avoid this electrified zone and to follow along the upstream electrode at the fringe of the electrical field. Any fish that entered the uniform field between the two rows of electrodes got a sudden shock and because of the galvanotropic nature of the stimulus, tended to turn so that they headed upstream towards the positive electrode. As shown in Table 4,

TABLE 4

EFFICIENCIES OF GUIDING WITH A GALVANOTROPIC SCREEN USING INTERRUPTED DIRECT CURRENT, 4 PPS, 75% DUTY CYCLE.

| Date | Time | | Voltage Gradient v/in. | Total Fish | Guiding Efficiency (per cent) | Remarks |
|---|---|---|---|---|---|---|
| | Start | End | | | | |
| 1953 | | | | | *Repulsion* | |
| April | | | | | | |
| 30 | 5:50 p.m. | 6:10 p.m. | 1.67 | 1,291 | 99.4 | Slight immobilization. |
| 30 | 7:18 p.m. | 7:37 p.m. | 1.67 | 2,476 | 97.9 | Slight immobilization. |
| May | | | | | | |
| 1 | 2:17 p.m. | 2:46 p.m. | 1.67 | 3,174 | 96.7 | Slight immobilization. |
| 1 | 8:02 p.m. | 9:10 p.m. | 1.00 | 212 | 27.0 | Fish escaped easily. |
| 2 | 7:30 p.m. | 7:47 p.m. | 2.50 | 133 | 92.1 | Severe immobilization. |
| Average efficiency using 1.67 v/in. | | | | | 97.6 | |

the average efficiency in diverting the fish was 97.6 per cent, using interrupted direct current at a nominal voltage gradient of 1.67 volts per inch (peak voltage of 40, divided by 24 inches between electrodes), 4 pulses per second and a duty cycle of 75 per cent. That is, 97.6 per cent of the fish that would normally have entered the left trap were repelled by the galvanotropic screen.

An important aspect of the problem of guiding fish electrically is the effect of electrical exposure on survival. It was therefore important to examine the reaction of the fish during the tests. Interrupted direct current, 1.67 volts per inch, 4 pulses per second, 75 per cent duty cycle, caused practically no immediate mortality in any of the tests. Some of the fish that were swept too close to an electrode were temporarily immobilized but they usually recovered their equilibrium within a few seconds. Nearly all the fish avoided the fringe currents immediately upstream from the anode row of electrodes. Schools of fish swam along the upstream face of the anode row but few fish ventured to within 6 inches of an electrode. However, some large schools entering the test area swam downstream towards the electrode array without hesitation and when these fast-moving schools reached the electrodes the foremost fish penetrated the electrified zone, probably as a result of crowding, but the remainder retreated upstream. Practically all those that entered the electrified zone were attracted back upstream by the galvanotropic stimulus, but occasionally the swimming ability of some of them was greatly impaired by electrical shock and they had considerable difficulty in swimming upstream. A few were so impaired that they were swept through the electrified zone by the water velocity but most of these fish recovered immediately and returned upstream to rejoin the masses of fish on the upstream side of the electrodes. One important reason for the effectiveness of this type of electrical screen must be emphasized: the fish swim *upstream* through the electrified area with comparative ease, whereas they have great difficulty in swimming towards the cathode or negative electrode to escape *downstream* through the electrified area.

Observations indicated that only a small proportion of the fish that were guided received the full intensity of the electric shock and the survival of these fish did not appear to be seriously affected. The three fish captured in the trap behind the electrodes after the test at 5:50 p.m. on April 30, (Table 4) were immobilized when they entered the trap but two of them recovered almost immediately and seemed in excellent condition. The third regained its equilibrium in a short time but remained inactive.

This method of screening fish electrically is unique. In the past, parallel rows of electrodes have been placed across waterways but efficient galvanotropic stimuli have not been applied *to attract* the fish back upstream out of the electrified zone between the two rows of electrodes. McMillan (1928) used alternating current *to scare* the fish but Holmes (1948) shows that alternating current is not satisfactory because it tetanizes the muscles of the fish, thereby making swimming impossible and the fish are then carried through the screen by the water velocity. To differentiate the electric screen used in the experiments at Cultus Lake in 1953 from those used in previous experiments, the arrangement of two parallel rows

of closely spaced electrodes energized by an efficient galvanotropic stimulus to attract fish out of the electrified zone has been called a "galvanotropic screen".

Experiments were also conducted using 60-cycle alternating current to energize the two closely spaced rows of electrodes. In these, many fish were scared upstream but a large proportion of the fish were immobilized by the electric current and swept through the electrified zone by the water velocity. Voltages that were low enough to prevent rapid immobilization were not of sufficient intensity to scare or repel the fish efficiently.

Other experiments suggested that the repetitive discharging of a condenser was not an efficient galvanotropic stimulus. At a peak intensity of 2.8 volts per inch the discharging of a 45 microfarad condenser at 4 pulses per second across the electrode array did not stop the fish. Fish passed through the electric field with apparent ease and very few were guided along the upstream row of electrodes. At higher voltages some fish were attracted back upstream, but many continued to swim through the electrified area.

It was concluded from these experiments that electrical stimuli showed definite promise for guiding downstream-migrant sockeye and that the most efficient guiding would be obtained when two closely spaced parallel rows of electrodes were energized with an effective galvanotropic stimulus such as interrupted direct current.

### Other Methods

It was suggested that underwater vibrations might be used to warn fish of impending danger or to attract them. However, Burner and Moore (1953) using various frequencies and intensities of underwater vibrations in experiments with trout showed that fright reactions were produced only when the vibration was first applied. Since the fish soon became accustomed to the sound, it had no guiding effect. Brett, *et al* (1954) used a variable-frequency oscillator and a subsurface transducer in experiments with yearling sockeye salmon and found that the fish exhibited no response whatever to underwater vibrations from 1,000 to 10,000 cycles per second.

Visible barriers such as hanging chain deflectors have been used with some success in guiding downstream-migrant sockeye in small-scale experiments. Brett, *et al* (1954) showed that downstream-migrant sockeye tended to be deflected away from a barrier formed by hanging three-sixteenth-inch "safety" chain at close intervals from the surface to the bottom of a stream. Coho *(O. kisutch)* did not appear to be guided as effectively as sockeye. Fields, *et al* (1954) reported that significant deflection was not obtained with hanging chains in still water. Cooper (1952) found that moving objects such as hanging rods and bright objects such as white flashboards were only partially effective in preventing downstream-migrant sockeye from entering an opening in a wire-screen fence. Observations made at Cultus Lake in 1954 showed that hanging chains spaced six inches apart were completely ineffective as a guiding method in moving water.

### Comparison of Relative Guiding Efficiencies

Figure 6 gives a graphic comparison of the relative guiding efficiencies obtained in the field experiments at Cultus Lake in 1953. The tests conducted with veils of air bubbles showed that fish were consistently attracted to the bubbles during daylight but were repelled during darkness. The fish were also repelled during darkness when the bubbles were illuminated. The wide range in efficiencies in all of the air bubble tests indicated that there was very little possibility that air bubbles could be used successfully to guide downstream-migrant sockeye. Surface lights also gave inconsistent results but a significant attraction was obtained with subsurface spotlights. A shaded or protective passageway was partially effective during daylight. Excellent results were obtained with the galvanotropic screen.

Since yearling sockeye possess a strong urge to move downstream in their journey from the lake rearing area to the ocean it would be necessary to employ

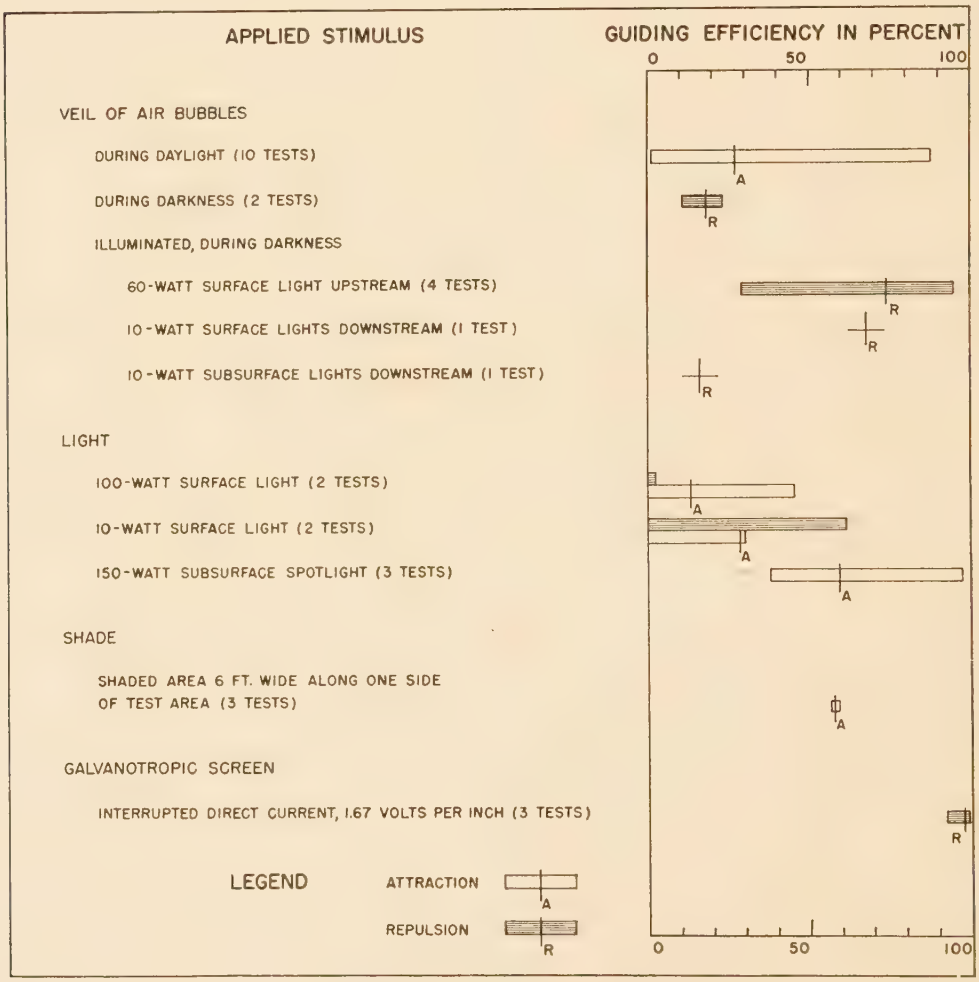


FIGURE 6. Relative guiding efficiencies of various possible methods of guiding downstream-migrant sockeye. (The length of the bar indicates the range of efficiencies obtained in the tests and the line crossing the bar shows the weighted average efficiency.)

a very positive stimulus in order to guide them away from hazardous areas. Their migratory urge is so strong that sockeye tend to force their way past various obstacles. For instance, early experiments with electric screens showed that despite the stresses imposed by electrical exposure fish continually tried to force their way through electrical barriers (Holmes, 1948). Some fish were carried through the screen in a narcotized condition, other fish were killed. Similarly, at mechanical wire screens, their persistence in moving downstream is so pronounced that downstream-migrant salmon can force their way through screen apertures that are slightly smaller than the width of their bodies (Chapman, 1935). Fish also tend to ride over the top of a rotating cylindrical wire screen when they find their downstream passage blocked. It appears therefore that it will be difficult, if not impossible, to develop methods of applying artificial stimuli to give 100 per cent efficiency in guiding various species and sizes of fish past hazardous areas at large dams.

The possibilities that sound, visible barriers, changes in water velocity, chemicals, magnetism and conditioned response might be used as guiding methods have not been thoroughly studied but these methods do not appear to offer much promise for large-scale field applications. Lights, shade, air bubbles and visible barriers may be of some value for increasing the effectiveness of by-passes but the galvanotropic screen is the only method that has been found successful in these experiments for *forcing* fish to stay away from certain areas.

## FACTORS INFLUENCING EFFICIENCY OF ELECTRIC FISH SCREENS

The 1953 experiments indicated that galvanotropic screens offered more promise than the other guiding methods studied, and therefore a more comprehensive investigation of this method was conducted at Cultus Lake in the spring of 1954. This study was conducted to confirm the high guiding efficiencies obtained in the 1953 experiments and to investigate the relative effectiveness of various electrical stimuli and electrode arrangements. Most of the tests were conducted in a flume but a few were also conducted to determine the efficiency of a galvanotropic screen for guiding fish across the entire width of Sweltzer Creek.

As shown in Figure 7, the flume in which the experiments were conducted was built near the left bank of Sweltzer Creek immediately downstream from a 110-foot long wire-screen fence spanning the creek. A 2-foot dam was also built across the creek to maintain a uniform depth of approximately 2.3 feet of water in the test area. The flume was 16 feet wide and 36 feet long; its sides were built of 2-inch plank 3 feet high, and the bottom of 1-inch lumber laid over 2- by 12-inch stringers, and it was all lined with ¼-inch plywood insulated with green marine paint. The downstream end consisted of an adjustable dam that enabled the velocity of the flowing water to be controlled. A ¼-inch mesh webbing barrier was placed upstream from the dam to prevent fish from escaping. Two removable wire-screen gates were provided at the entrance to the flume. Two inclined-plane wire-screen traps, 4 feet wide, 8 feet long and 12 inches deep, were attached to the test area. The entrance to one (the spillway trap) was a submerged slot at

the extreme left of the downstream wall of the flume and the entrance to the other (the by-pass trap) was a slot in the right wall about 8 feet upstream. Each slot was 48 inches wide and had its lower edge 12 inches above the floor of the test area, the slot to the spillway trap being 6 inches high and that to the by-pass trap being 3 inches. Vertical-sliding gates were used to open and close the slots. These traps were similar to those used in the 1953 experiments but addition of

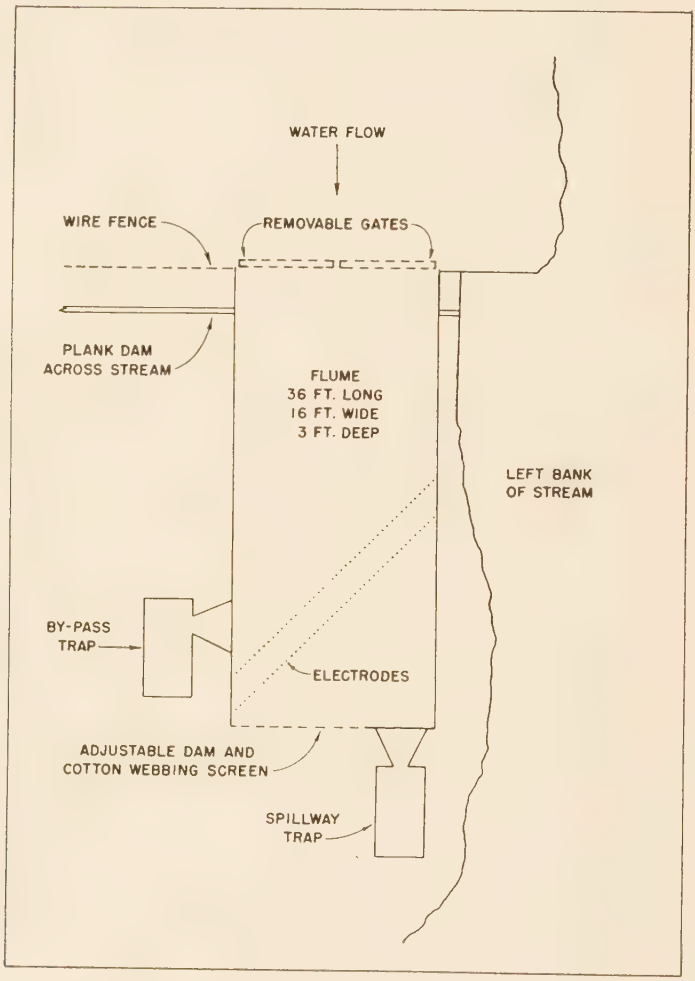


FIGURE 7. Test area used in Sweltzer Creek in 1954.

the watertight sliding gates facilitated removal of fish at the end of each test. A piece of ¼-inch wire screen, 8 feet by 16 feet, was placed on a slope at the upstream end of the test area so that fish moving downstream were gradually led to within 12 inches of the water surface before reaching the test area. The fish moved downstream into the test area without hesitation and did not readily escape upstream again. The entire test area was covered to eliminate local shaded areas.

Electrodes were placed across the entire width of the flume and tests were conducted to determine whether they could effectively keep all fish away from the spillway trap and divert them into the by-pass trap.

Water velocities in the flume were measured periodically with a bucket-type (Price) current meter. These measurements were taken at two depths at intervals of about two feet along a line midway between the two rows of electrodes. These data are summarized in Table 5. Although the velocities at the electrodes were fairly uniform, there were some unavoidable variations in localized areas because of the proximity of the electrodes to the trap entrances.

TABLE 5

WATER VELOCITIES MIDWAY BETWEEN THE TWO ROWS OF ELECTRODES IN THE TEST AREA DURING THE USUAL TEST CONDITION IN 1954

| | *Water Velocities (Feet Per Second)* | | |
|---|---|---|---|
| | | *Range* | |
| | *Average* | *Maximum* | *Minimum* |
| April 22 | 0.32 | 0.48 | 0.16 |
| May 5 | 0.27 | 0.46 | 0 |
| May 12 | 0.40 | 0.53 | 0.17 |
| May 25 | 0.36 | 0.70 | 0.13 |
| Average 0.34 feet per second | | | |

The resistivity, or specific resistance, of the water was also measured at frequent intervals during the experiment because it had been shown previously that the galvanotropic response was influenced by water resistivity. An Industrial Instruments Type RC Conductivity Bridge with a neoprene dip cell (cell constant = 1) was used for this purpose. The data, presented in Table 6, show that the average specific resistance during the experiment was 3,360 ohms per inch-cube. Daily maximum and minimum water temperatures were also measured because it was thought that the response of fish might be affected by temperature. At the beginning of the tests on April 20 the average temperature was 43°F. but as the season progressed, it gradually increased until at the end of the experiment, on May 25, it reached 55°F.

Since the voltage gradient required to produce galvanotropism is dependent on fish size, length measurements of the fish were made periodically throughout the experiment. There was very little range in size, however, because the population consisted of only a very small proportion of two-year olds and all of these were rejected from the trap catches. On April 21, measurements of a sample of 232 yearling sockeye showed that the average fork length was 3.42 inches, with a maximum of 4.01 inches and a minimum of 2.68 inches. Another sample of 215 yearlings taken on May 2 showed that the average length had decreased to 3.20 inches, with a maximum measurement of 3.82 and a minimum of 2.44.

TABLE 6

SPECIFIC RESISTANCE OF SWELTZER CREEK WATER DURING EXPERIMENTS IN 1954

| | *Specific Resistance Ohms per inch-cube* | *Temperature °F.* |
|---|---|---|
| April 20 | 3,740 | 43 |
| 21 | 3,420 | 45 |
| 22 | 3,380 | 45 |
| 22 | 3,480 | 45 |
| 25 | 3,310 | 45 |
| 25 | 3,420 | 45 |
| 26 | 3,440 | 44 |
| 27 | 3,470 | 42 |
| May 2 | 3,580 | 44 |
| 3 | 3,400 | 46 |
| 14 | 3,420 | 48 |
| 17 | 3,050 | 50 |
| 22 | 2,960 | 56 |
| 23 | 2,910 | 55 |
| Average | 3,360 | 47 |

The procedure used in the 1954 experiments was very similar to that used in the 1953 study. Control runs were made to measure the normal distribution of fish between the two traps so that when the electrodes were energized the percentage of fish actually guided by the stimulus could be computed in the manner previously described for the 1953 experiments.

All test and control runs were conducted in the same manner. The entrance gates at the upstream end of the flume were opened and any fish present in the area beyond the electrodes were scared to the upstream end of the flume before the gates to the traps were raised. When a large number of fish had accumulated in the traps, the gates were closed simultaneously. The fish were then removed from the traps and counted.

Catches of less than 500 fish were usually counted individually but the majority of the fish were counted volumetrically. For this purpose a steel cylindrical can, 8 inches in diameter and 40 inches deep, with a capacity of about 1,500 fish, was used. A glass gauge on the outside enabled the vertical displacement of the water surface to be read to the nearest millimeter, and daily calibration ensured accurate computation of the numbers of fish.

The normal distribution of fish between the two traps was measured in 92 control runs. The total number of fish involved in these controls was 212,600, of which 59.47 per cent entered the spillway trap. Since this was significantly different from a 50 per cent distribution, and the 95 per cent confidence interval was only $\pm 3.42$ per cent, this value was accepted as the standard for computing guiding efficiencies.

Tests were conducted using the following electrical stimuli to energize the galvanotropic screen:

1. *Direct current* obtained from two compound-wound direct-current generators. The most frequently used generator had a capacity of 1.5 kilowatts, the other had a capacity of 5 kilowatts. By connecting the two generators in series, up to 300 volts output could be obtained.

2. *Interrupted direct current* usually obtained by inserting the previously described rotating switch between the direct current generators and the electrodes. In a large-scale experiment where higher currents were involved, an electronic method, which will be described later, was required in order to avoid excessive arcing at the contacts in the rotary switch. The rotating switch, however, was an entirely satisfactory and very convenient apparatus for interrupting direct current for the tests in the 16-foot flume where the required current did not exceed 7 amperes.

3. *Rectified 60-cycle alternating current* obtained by the use of an isolating transformer and thyratron rectifier tubes supplied from a 60-cycle single-phase source. Both full-wave and half-wave rectification were used.

4. *Rectified 400-cycle alternating current* obtained by the use of thyratron rectifier tubes supplied from a 1-kilowatt 400-cycle alternating-current generator.

5. *Interrupted rectified alternating current* obtained by using a variable-speed motor-driven switch to change the bias on the grids of the thyratron rectifier tubes. Both 60-cycle and 400-cycle full-wave rectified alternating current were used.

6. *Condenser discharge impulses* obtained by charging a condenser from a 440-volt alternating current source through a diode rectifier and discharging this condenser through a thyratron to the electrodes. The discharge of the condenser was initiated by instantaneously changing the bias on the grid of the thyratron by means of a motor-driven rotating switch.

The results of the tests are presented in Tables 7 to 15. Except as noted, all guiding efficiencies indicate repulsion from the electric screen. A table is given for each electrode arrangement tested and within each table the tests have been classified according to the electrical stimulus and arranged in ascending order of voltage gradient. The tests were not conducted in the order in which they are listed in the tables. The electrical stimuli and voltage gradients were selected more or less at random during the experiments. Often several tests were conducted under the same experimental conditions and as the guiding efficiencies obtained under parallel conditions varied only very slightly the numbers of fish in these tests have been combined to give a single guiding efficiency.

Observations of the activity of the fish during the tests were found to be very important in assessing the guiding effectiveness of the various electrode arrangements and electrical stimuli. The degree of galvanotropism was recorded in five classifications: excellent, good, fair, poor and none. When practically all of the fish turned upstream after entering only a few inches into the electrified

zone this was classified as "excellent" tropism. "Good" tropism indicates that practically all of the fish turned upstream before they had travelled half the distance between the two electrode rows. When the turning was not very definite or when many fish swam as far as the downstream row of electrodes before turning, this was classified as "fair" tropism. "Poor" indicates that many fish did not exhibit galvanotropism.

Another important observation was the extent of immobilization. This was listed in the tables in four classifications: severe, considerable, slight and none. When some fish were killed or when the swimming ability of many of the fish was greatly impaired, this was classified as "severe" immobilization. It was observed that in many cases a large proportion of the fish were immobilized by excessively high voltage gradients, especially near the electrodes. Some of these fish were killed when they were unable to escape from the high concentration of current at an electrode or when they settled and remained on the bottom in the electrified zone. When the swimming ability of the fish was greatly impaired they were involuntarily attracted to an anode electrode, where they received a severe

TABLE 7

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH ⅛-INCH DIAMETER ELECTRODES, 24 INCHES BETWEEN ELECTRODE ROWS, 6-INCH SPACING IN EACH ROW, 60° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Stimulus:* Interrupted direct current, 4 pps, 75 to 80% duty cycle. | | | | | |
| 1.00 | 379 | 59.63 | 32.00 | Poor | None |
| 1.50 | 1,435 | 94.77 | 91.21 | Fair | None |
| 1.67 | 7,428 | 89.35 | 82.09 | Good | Slight |
| 2.00 | 1,409 | 85.80 | 76.13 | Good | Considerable |
| 3.00 | 1,010 | 86.44 | 77.21 | Good | Severe |
| *Stimulus:* Direct current. | | | | | |
| 1.67 | 1,386 | 86.36 | 77.06 | Excellent | Slight |
| 2.00 | 1,619 | 90.49 | 84.01 | Good | Considerable |
| 2.50 | 882 | 85.94 | 76.34 | Excellent | Severe |
| *Stimulus:* Full-wave rectified 400-cycle alternating current. | | | | | |
| 1.25 | 3,547 | 75.44 | 58.70 | Poor | None |
| 1.67 | 1,865 | 83.70 | 72.59 | Fair | None |
| 2.08 | 2,786 | 94.11 | 90.10 | Good | Considerable |
| 2.50 | 1,957 | 89.07 | 81.62 | Good | Severe |
| *Stimulus:* Condenser discharge, 125 microfarads, 4 to 8 pps. | | | | | |
| 4.58(4 pps) | 869 | 87.23 | 78.53 | Poor | None |
| 7.50(7.5 pps) | 3,391 | 64.32 | 40.00 | Poor | Slight |
| 10.00(4 pps) | 819 | 77.53 | 62.22 | Poor | Slight |
| 11.25(8 pps) | 1,900 | 34.21 | 15.58* | Poor | Considerable |

* Fish were attracted instead of being repelled by the electric screen.

electric shock. This degree of immobilization would not be permissable at a practical installation because fish that were being guided over a longer distance might be permanently weakened as a result of the cumulative effect of repeated exposures. "Considerable" immobilization was also a serious condition. This classification indicated that practically no fish were killed but that the swimming ability of some was greatly impaired and many exhibited a temporary loss of equilibrium. This degree of immobilization, therefore, would also be undesirable at a practical installation. "Slight" immobilization indicated that no fish were killed but that there was some loss of equilibrium. Although these classifications are arbitrary, they are helpful in isolating conditions that appeared to be harmful to the fish.

TABLE 8

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH ⅛-INCH DIAMETER ELECTRODES, 48 INCHES BETWEEN ELECTRODE ROWS, 6-INCH SPACING IN EACH ROW, 60° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 0.75 | 1,236 | 67.64 | 45.58 | Poor | None |
| 0.83 | 1,019 | 85.48 | 75.58 | Poor | Slight |
| 1.00 | 5,614 | 85.38 | 75.42 | Fair | Considerable |
| 1.25 | 1,709 | 91.11 | 85.04 | Excellent | Considerable |
| 1.50 | 2,336 | 84.55 | 74.01 | Excellent | Severe |
| *Stimulus:* Direct current. | | | | | |
| 0.75 | 1,573 | 62.68 | 37.22 | Poor | None |
| 1.00 | 840 | 83.57 | 72.40 | Fair | None |
| 1.12 | 1,293 | 84.15 | 73.34 | Fair | Slight |
| *Stimulus:* Interrupted direct current, 4 pps, 95% duty cycle. | | | | | |
| 0.83 | 3,564 | 77.08 | 61.44 | Fair | Slight |
| 1.00 | 1,125 | 80.53 | 67.27 | Fair | Slight |
| 1.12 | 2,010 | 87.61 | 79.16 | Good | Considerable |
| *Stimulus:* Interrupted full-wave rectified 400-cycle alternating current, 4 pps, 80% duty cycle. | | | | | |
| 1.25 | 1,924 | 74.64 | 57.34 | Poor | None |
| 1.50 | 1,508 | 78.18 | 63.32 | Poor | Severe |
| *Stimulus:* Full-wave rectified 400-cycle alternating current. | | | | | |
| 1.00 | 1,902 | 32.18 | 20.62* | Poor | None |
| 1.12 | 1,468 | 60.90 | 34.25 | Poor | None |
| 1.25 | 477 | 82.60 | 70.78 | Fair | Slight |
| 1.50 | 1,369 | 80.20 | 66.71 | Fair | Considerable |
| *Stimulus:* Condenser discharge, 4 to 12 pps. | | | | | |
| 5.83 (4 pps) | 359 | 56.55 | 26.76 | Poor | None |
| 5.83 (12 pps) | 1,235 | 46.88 | 10.63 | Fair | Severe |
| 7.00 (4 pps) | 2,160 | 50.05 | 15.97 | Poor | None |
| 7.29 (8 pps) | 1,029 | 45.68 | 8.66 | Fair | Considerable |

* Fish were attracted instead of being repelled by the electric screen.

TABLE 9

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH WIRE MESH ELECTRODES, 1/32-INCH DIAMETER WIRE, MESH SIZE 6 INCHES BY 4 INCHES, 48 INCHES BETWEEN ELECTRODE ROWS, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 1,271 | 95.52 | 92.46 | Good | None |
| 1.12 | 1,512 | 97.82 | 96.33 | Good | Slight |
| 1.25 | 1,783 | 97.70 | 96.13 | Excellent | Slight |
| 1.50 | 1,029 | 98.83 | 98.03 | Excellent | Considerable |
| *Stimulus:* Direct current. | | | | | |
| 1.00 | 832 | 99.64 | 99.39 | Fair | None |
| 1.12 | 2,698 | 89.62 | 82.54 | Poor | Slight |
| 1.25 | 2,437 | 98.11 | 96.83 | Good | Slight |
| 1.50 | 1,675 | 98.09 | 96.79 | Excellent | Severe |
| *Stimulus:* Interrupted full-wave rectified 400-cycle alternating current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 1,451 | 69.95 | 49.48 | Poor | Considerable |
| 1.25 | 2,321 | 80.14 | 66.59 | Poor | Severe |
| 2.08 | 913 | 98.58 | 97.61 | Good | Severe |
| *Stimulus:* Full-wave rectified 400-cycle alternating current. | | | | | |
| 1.00 | 1,314 | 68.65 | 47.25 | None | Severe |
| 1.25 | 987 | 95.44 | 92.33 | Poor | Severe |
| *Stimulus:* Interrupted full-wave rectified 60-cycle alternating current, 4 pps, 10 and 80% duty cycles. | | | | | |
| 0.62 (10%) | 666 | 82.13 | 69.95 | None | Severe |
| 0.62 (80%) | 891 | 74.41 | 56.98 | Poor | Severe |
| 1.00 (80%) | 811 | 85.70 | 75.93 | Poor | Severe |
| *Stimulus:* Interrupted direct current, 4 pps, 10% duty cycle. | | | | | |
| 1.50 | 137 | 72.99 | 54.32 | Fair | None |
| 1.75 | 260 | 84.62 | 74.19 | Fair | Slight |
| 2.00 | 151 | 86.09 | 76.66 | Fair | Slight |
| *Stimulus:* Interrupted direct current, 9 pps, 30% duty cycle. | | | | | |
| 1.00 | 1,382 | 84.95 | 74.70 | Poor | Slight |
| 1.25 | 821 | 83.19 | 71.72 | Fair | Slight |
| 1.50 | 391 | 94.89 | 91.40 | Fair | Slight |
| 1.75 | 646 | 97.06 | 95.05 | Excellent | Slight |
| 2.00 | 1,004 | 98.80 | 97.99 | Excellent | Considerable |
| 2.25 | 764 | 96.47 | 94.05 | Excellent | Severe |
| *Stimulus:* Interrupted direct current, 2 to 9 pps, 50% duty cycle. | | | | | |
| 1.12 (2 pps) | 815 | 92.15 | 86.80 | Fair | Severe |
| 1.12 (4 pps) | 845 | 92.07 | 86.65 | Poor | Severe |
| 1.12 (7 pps) | 1,985 | 96.27 | 93.73 | Fair | Severe |
| 1.12 (9 pps) | 1,083 | 96.68 | 94.41 | Poor | Severe |

TABLE 10

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH 3/16-INCH HANGING CHAIN ELECTRODES, 24-INCH DISTANCE BETWEEN ROWS, INTERRUPTED DIRECT CURRENT, 4 PPS, 80% DUTY CYCLE, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Electrodes:* 6-inch spacing in each row. | | | | | |
| 1.50 | 1,083 | 95.20 | 91.93 | Fair | None |
| 1.67 | 1,491 | 97.79 | 96.28 | Good | Slight |
| 2.00 | 754 | 97.75 | 96.20 | Excellent | Severe |
| *Electrodes:* 12-inch spacing in each row, staggered. | | | | | |
| 1.00 | 2,220 | 68.38 | 46.82 | None | None |
| 1.50 | 1,179 | 99.83 | 99.71 | Good | None |
| 1.67 | 2,325 | 99.53 | 99.21 | Excellent | None |
| 2.00 | 2,418 | 99.01 | 98.33 | Excellent | Considerable |
| *Electrodes:* 18-inch spacing in each row, not staggered. | | | | | |
| 1.50 | 1,255 | 95.06 | 91.68 | Poor | None |
| 1.67 | 1,250 | 99.20 | 98.65 | Fair | None |
| 2.00 | 1,228 | 98.29 | 97.12 | Good | Considerable |
| *Electrodes:* 18-inch spacing in each row, staggered. | | | | | |
| 1.67 | 426 | 98.59 | 97.63 | Fair | None |
| *Electrodes:* 24-inch spacing in each row, not staggered. | | | | | |
| 1.67 | 972 | 92.28 | 87.00 | Poor | Considerable |
| 2.00 | 972 | 95.47 | 92.37 | Fair | Severe |
| *Electrodes:* 24-inch spacing in each row, staggered. | | | | | |
| 1.50 | 1,145 | 52.58 | 20.15 | None | None |
| 2.00 | 531 | 96.99 | 94.94 | Fair | Considerable |
| 2.50 | 1,091 | 98.99 | 98.30 | Fair | Considerable |
| 3.00 | 400 | 94.50 | 90.76 | Fair | Severe |
| *Electrodes:* 36-inch spacing in each row, staggered. | | | | | |
| 2.00 | 795 | 83.65 | 72.51 | Poor | Slight |
| 2.50 | 978 | 93.25 | 88.66 | Poor | Severe |

Although many tests were conducted in which severe immobilization was noted, less than 500 fish were killed as a result of electrical exposure during these experiments. All tests that produced "severe" immobilization were ended as soon as the extent of immobilization became evident.

In comparing the effectiveness of one combination of electrode arrangement and electrical stimulus with another combination from the data given in Tables 7 to 15 it is necessary to consider the maximum practical efficiency obtainable with each combination. All the tables show that as the voltage gradient increases, the extent of immobilization increases and galvanotropism also increases, within limits. For each combination of electrode arrangement and electrical stimulus

TABLE 11

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH 3/16-INCH HANGING CHAIN ELECTRODES, 48-INCH DISTANCE BETWEEN ROWS, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Electrodes:* 6-inch spacing in each row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 1,515 | 73.14 | 54.83 | Fair | None |
| 1.12 | 1,166 | 86.88 | 77.92 | Fair | Considerable |
| 1.25 | 1,409 | 92.76 | 87.83 | Fair | Severe |
| *Electrodes:* 12-inch spacing in each row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 674 | 50.74 | 17.21 | Poor | None |
| 1.12 | 1,326 | 72.47 | 53.71 | Poor | None |
| 1.25 | 1,736 | 87.50 | 78.98 | Excellent | Slight |
| 1.37 | 669 | 98.36 | 97.24 | Excellent | Slight |
| *Stimulus:* Direct current. | | | | | |
| 1.37 | 307 | 89.58 | 82.51 | Fair | None |
| 1.50 | 773 | 99.48 | 99.13 | Excellent | Slight |
| 1.62 | 625 | 98.88 | 98.12 | Excellent | Slight |
| *Stimulus:* Interrupted direct current, 4 pps, 30% duty cycle. | | | | | |
| 1.25 | 743 | 96.50 | 94.12 | Fair | None |
| 1.50 | 954 | 83.75 | 72.66 | Fair | Considerable |
| *Stimulus:* Interrupted direct current, 4 pps, 50% duty cycle. | | | | | |
| 1.75 | 126 | 92.86 | 88.00 | Fair | Considerable |

there is a certain maximum voltage gradient that can be used without producing excessive immobilization. The guiding efficiency achieved at this optimum voltage gradient may be considered as being the maximum practical efficiency obtainable with the given set of experimental conditions. Comparison of the maximum practical efficiencies obtained under two sets of conditions will therefore give a good measure of the relative effectiveness of the two conditions but comparison of the efficiencies obtained at a specific voltage gradient will not. It must also be borne in mind that some fish after escaping through the electric screen returned upstream and were therefore not captured in the spillway trap but it is not known whether they would have returned upstream if they had not been confined in the small area between the electrodes and the downstream end of the flume. So many fish escaped through the electric screen in some of the tests when the galvanotropism was classified as "none" or "poor" that it is likely that they would have formed schools and continued moving downstream if they had not been confined. Therefore the maximum practical efficiency that must be used

TABLE 12

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME WITH 1-INCH DIAMETER ELECTRODES, 24-INCH DISTANCE BETWEEN ROWS, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Electrodes:* 12-inch spacing in each row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 1,822 | 30.08 | 25.85* | None | None |
| 1.33 | 4,324 | 89.50 | 82.34 | Poor | None |
| 1.50 | 1,597 | 91.80 | 86.21 | Poor | Slight |
| 1.67 | 4,402 | 96.37 | 93.89 | Fair | Slight |
| 2.00 | 3,005 | 94.64 | 90.99 | Fair | Considerable |
| 2.25 | 1,265 | 99.60 | 99.34 | Excellent | Severe |
| *Stimulus:* Direct current. | | | | | |
| 1.00 | 3,128 | 26.95 | 33.52* | None | None |
| 1.50 | 2,425 | 96.41 | 93.97 | Fair | Slight |
| 2.00 | 1,333 | 98.27 | 97.10 | Excellent | Severe |
| 2.25 | 1,802 | 98.28 | 97.11 | Excellent | Severe |
| *Electrodes:* 24-inch spacing in each row, staggered. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.50 | 1,229 | 83.97 | 73.05 | Fair | None |
| 1.67 | 3,028 | 97.52 | 95.89 | Fair | Slight |
| 2.50 | 1,153 | 85.69 | 75.95 | Good | Severe |
| *Electrodes:* 24-inch spacing in upstream row, 12-inch spacing in downstream row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.67 | 2,868 | 95.54 | 92.50 | Good | Slight |
| 1.87 | 2,097 | 92.51 | 87.97 | Good | Considerable |

* Fish were attracted instead of being repelled by the electric screen.

TABLE 13

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME, WITH 1-INCH DIAMETER ELECTRODES, 36-INCH DISTANCE BETWEEN ROWS, 12-INCH SPACING IN EACH ROW, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 5,016 | 82.78 | 71.04 | Poor | Slight |
| 1.11 | 1,981 | 85.26 | 75.21 | Poor | Slight |
| 1.25 | 1,395 | 75.34 | 58.55 | Poor | Slight |
| 1.33 | 6,722 | 95.30 | 92.10 | Fair | Considerable |
| 1.50 | 7,230 | 97.44 | 95.70 | Good | Severe |
| 2.00 | 251 | 96.02 | 93.29 | Good | Severe |
| *Stimulus:* Direct current. | | | | | |
| 0.44 | 899 | 43.27 | 4.67 | None | None |
| 1.00 | 1,267 | 75.30 | 58.43 | Poor | None |
| 1.25 | 1,467 | 87.25 | 78.56 | Fair | Slight |
| 1.33 | 2,314 | 89.84 | 82.92 | Fair | Severe |
| 1.50 | 10,785 | 97.39 | 95.60 | Good | Severe |

in comparisons to obtain a measure of the relative efficiency of various combinations of electrode arrangement and electrical stimuli is the maximum guiding efficiency obtained when the immobilization was classified as "none" or "slight" and the galvanotropism was classified as "excellent," "good," or "fair."

TABLE 14

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME, WITH 1-INCH DIAMETER ELECTRODES, 48-INCH DISTANCE BETWEEN ROWS, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Electrodes:* 12-inch spacing in each row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 4,735 | 85.72 | 75.99 | Fair | None |
| 1.12 | 770 | 98.96 | 98.25 | Good | Slight |
| 1.25 | 5,930 | 95.36 | 92.20 | Good | Considerable |
| 1.50 | 5,105 | 97.08 | 95.09 | Good | Severe |
| 1.67 | 734 | 97.41 | 95.64 | Good | Severe |
| 2.00 | 644 | 98.29 | 97.13 | Good | Severe |
| *Stimulus:* Direct current. | | | | | |
| 1.00 | 2,607 | 17.07 | 57.89* | Poor | None |
| 1.12 | 1,997 | 99.90 | 99.83 | Fair | Slight |
| 1.25 | 1,526 | 99.21 | 98.67 | Good | Slight |
| 1.50 | 2,197 | 94.58 | 90.89 | Good | Considerable |
| 2.00 | 632 | 96.52 | 94.15 | Good | Severe |
| *Stimulus:* Interrupted direct current, 8 pps, 80% duty cycle. | | | | | |
| 1.00 | 969 | 85.35 | 73.35 | Poor | Slight |
| 1.12 | 862 | 96.40 | 93.96 | Good | None |
| 1.25 | 788 | 95.18 | 91.90 | Good | Considerable |
| 1.50 | 348 | 97.70 | 96.14 | Good | Considerable |
| *Stimulus:* Interrupted direct current, 9 pps, 30% duty cycle. | | | | | |
| 1.50 | 713 | 90.04 | 83.25 | Fair | Considerable |
| 2.00 | 707 | 93.64 | 89.29 | Fair | Severe |
| *Stimulus:* Interrupted full-wave rectified 400-cycle alternating current, 4 pps, 80% duty cycle. | | | | | |
| 2.50 | 382 | 99.21 | 98.68 | Fair | Severe |
| 3.00 | 64 | 79.69 | 65.79 | Fair | Severe |
| *Stimulus:* Full-wave rectified 400-cycle alternating current. | | | | | |
| 1.00 | 736 | 36.01 | 11.37* | None | None |
| *Electrodes:* 24-inch spacing in upstream row, 12-inch spacing in downstream row. | | | | | |
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.12 | 1,662 | 95.43 | 92.31 | Good | Slight |
| 1.50 | 377 | 87.00 | 78.13 | Good | Considerable |

* Fish were attracted instead of being repelled by the electric screen.

TABLE 15

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME, WITH 2½-INCH DIAMETER HORIZONTAL ELECTRODES, 24-INCH DISTANCE BETWEEN ROWS, 12-INCH SPACING IN EACH ROW, STAGGERED. 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Stimulus:* Interrupted direct current, 4 pps, 80% duty cycle. | | | | | |
| 1.00 | 1,710 | 68.42 | 46.90 | Poor | None |
| 1.25 | 1,675 | 99.64 | 99.40 | Fair | None |
| 1.50 | 1,174 | 97.96 | 96.56 | Good | Severe |
| 1.67 | 2,177 | 98.48 | 97.45 | Fair | Severe |
| *Stimulus:* Interrupted direct current, 7 pps, 40% duty cycle. | | | | | |
| 1.25 | 744 | 94.49 | 90.72 | Fair | None |

### Type of Electrical Stimulus

The relative effect of different types of electrical stimuli can be determined by comparing the maximum practical efficiencies achieved when a given electrode arrangement was energized with various stimuli. Interrupted direct current at a frequency of 4 pulses per second and a duty cycle of 80 per cent was a very effective stimulus. Continuous direct current was equally effective in most cases but it was observed that this stimulus appeared to cause more impairment of swimming ability. However, since it has been shown that the onset of the galvanotactic response precedes the onset of loss of equilibrium (Aserinsky, *et al,* 1954) this apparent increased impairment of swimming ability may be of little consequence provided the fish can orient themselves and swim out of the electrified zone in a very short period of time. Interrupted direct current at a frequency of 9 pulses per second and a 30 per cent duty cycle also produced very good guiding efficiencies but, as with direct current, there appeared to be more immobilization than when a frequency of 4 pulses per second and an 80 per cent duty cycle were used. Interrupted direct current at a duty cycle of 10 per cent produced a very poor guiding efficiency. In some tests full-wave rectified 400-cycle alternating current produced guiding efficiencies approximately equivalent to those obtained with direct current but in other tests it was observed that there was excessive immobilization. When this rectified 400-cycle current was interrupted, the guiding efficiencies were much lower than when interrupted direct current was used because the immobilization was so severe that the fish were unable to swim upstream out of the electrified zone. The primary frequency of 800 pulses per second (each pulse being one half of a sine wave), in combination with a secondary frequency of 4 pulses per second appeared to be intolerable. Interrupted full-wave rectified 60-cycle alternating current also produced a high degree of immobilization and good guiding efficiencies were therefore not achieved. The repetitive discharging of a condenser did not give good guiding efficiencies because the condenser discharge pulses were of such short duration that a good galvanotropic response was not obtained.

It is apparent that those stimuli that produced the greatest orientation to the positive electrode with the least impairment of swimming ability also produced the highest guiding efficiencies. Direct current and interrupted direct current, 4 pulses per second and 80 per cent duty cycle, or 9 pulses per second and 30 per cent duty cycle, gave high guiding efficiencies.

### Spacing of Electrodes in Each Row

The spacing of electrodes in each row has an important effect on the guiding efficiency because it influences the distribution of voltage gradient. It was observed in the 1953 experiments that in order to produce a distinct galvanotropic response without killing or immobilizing the fish a specific voltage gradient was required. If the gradient was too low some fish did not exhibit galvanotropism whereas if the gradient was too high some fish were immobilized or killed. It seemed likely therefore that a galvanotropic screen would be most effective if the optimum voltage gradient could be produced uniformly throughout the entire area between the two electrode rows. It would be impossible to produce a completely uniform voltage gradient in a practical galvanotropic screen because solid-plate electrodes (which would obviously be impractical) would be required and the flow of current between the two electrodes would have to be confined to a uniform cross-sectional area. Nevertheless, as an approach to uniformity was possibly desirable, and as it had been found that when vertical rod electrodes were spaced too far apart some fish were killed by the concentrated field near the electrodes, experiments were performed to determine what effect the spacing of electrodes within each row would have on the effectiveness of a galvanotropic screen.

Table 10 shows the results of a number of tests that were made with vertical chain electrodes at various spacings. Chains were used because they hung in a vertical position and the spacing between adjacent chains could be conveniently altered by sliding the chains along a horizontal conductor wire. Standard brass "safety chain" with links 3/16-inch wide and ½-inch long was used. The tests listed in Table 10 were made with 24 inches between the two electrode rows. Good results were obtained with a 6-inch or 12-inch interval in each row, the 12-inch giving slightly better results than the 6-inch. With an 18-inch spacing, large numbers of fish were able to escape between the electrodes whereas others were immobilized in the strong field near the anode. With a 24-inch spacing in each row, a higher voltage gradient was required and again many fish escaped quite easily and many were immobilized at the anode. More fish escaped and more were immobilized when a 36-inch spacing was used. It should be noted that when 18-, 24- and 36-inch spacings were used many fish were able to escape by passing midway between adjacent electrodes in a row but most of these fish were not caught in the spillway trap because they returned upstream by swimming through the electrified area again. The best guiding with the least immobilization was obtained when the spacing of electrodes in each row did not exceed 12 inches.

The effect of various electrode spacings within each row was also studied using hanging chain electrodes with 48 inches between the two rows. The results of these tests are given in Table 11. As 12-inch spacing in each row again gave

better results than a 6-inch spacing it seemed that a certain amount of field distortion might be desirable in order to provide a changing field intensity. The 6-inch spacing would provide a more uniform field intensity with less concentration of current at the electrodes but possibly the increased change in the field intensity near the electrodes with the 12-inch spacing acted as an added stimulus to induce the fish to turn and retreat upstream. With larger spacings, however, the field intensity near the electrodes was so great that many fish were immobilized.

The tests shown in Table 12 suggest that the 12-inch spacing gave about the same guiding efficiency as the 24-inch spacing but immobilization at the electrodes was more severe with 24-inch spacing. These tests were made with 1-inch diameter galvanized pipe electrodes at 24 inches between the two rows.

It was concluded that with small-diameter vertical electrodes at either 24 or 48 inches between the two rows, the highest guiding efficiency is obtained with a spacing of about 12 inches between the electrodes in each row.

### Distance Between the Two Electrode Rows

The distance between the two electrode rows also influences the effectiveness of a galvanotropic screen. Since the electrical field becomes more distorted as this distance is increased, fish would be immobilized at the electrodes if the rows were too far apart but, at the other extreme, if the rows were too close together fish would be swept through the electrified zone before they had time to respond to the galvanotropic stimulus. It is assumed therefore that for a given size and spacing of electrodes within each row there is an optimum distance between the two rows. Although this was not fully investigated in these tests, some evidence of the effect of distance between the two rows was obtained.

Tables 7 and 8 show that with ⅛-inch diameter wire electrodes at 6-inch intervals the guiding efficiencies were slightly higher with 24 than with 48 inches between rows. Similarly, Tables 10 and 11 show that with hanging chain electrodes at 6-inch intervals the efficiency was far higher with 24 inches between the rows than with 48 and that when the hanging chains were spaced at 12-inch intervals the efficiency was slightly higher with 24 inches between the rows than with 48 inches. On the other hand, further comparisons obtained from Tables 12, 13, and 14 show that with 1-inch diameter electrodes at 12-inch intervals a distance of 48 inches between rows gave slightly higher guiding efficiencies than either 24 or 36 inches.

These results suggested that the field distortion was less pronounced with the 1-inch diameter electrodes than with the ⅛-inch wire and 3/16-inch hanging chains and that greater distances could therefore be used between the two rows with the larger electrodes. A 24-inch distance gave slightly higher guiding efficiencies than the 48-inch distance when ⅛-inch wire or 3/16-inch chain electrodes were used but a 48-inch distance gave slightly higher guiding efficiencies than either a 24- or 36-inch distance when 1-inch diameter electrodes were used.

### Size of Electrodes

The effectiveness of the galvanotropic screen is also dependent upon the diameter or surface area of the electrodes since the distribution of voltage gradients at an electrode is dependent upon this diameter as well as upon the spacing between electrodes in each row and the distance between rows.

It is difficult to isolate the effect of electrode size but some information can be obtained from Tables 10, 12 and 15. Hanging chains, 1-inch pipes and 2½-inch pipes were used in comparable tests with a 12-inch spacing in each row and a 24-inch distance between rows. The best deflection was obtained with the 3/16-inch hanging chain electrodes. It may be noted that 1.67 volts per inch produced no immobilization with the hanging chain, slight immobilization with the 1-inch pipe and severe immobilization with the horizontal 2½-inch pipe. The large-diameter horizontal electrodes obstructed the escape of the fish from the electrified zone and many fish were attracted to the anode electrodes. Some fish hit the electrodes, were unable to escape, and were eventually immobilized. With small-diameter electrodes, either hanging chain or ⅛-inch wire, the fish were able to evade the electrodes and very few became immobilized.

The results in Tables 11 and 14 show, however, that there was very little, if any, difference in the results obtained with hanging chain electrodes and 1-inch pipe electrodes with 48 inches between the rows and a 12-inch spacing in each row. Table 9 shows that excellent results were also obtained with 1/32-inch diameter wire mesh electrodes.

High guiding efficiencies can therefore be obtained with small-diameter electrodes but with 2½-inch diameter horizontal electrodes many fish are immobilized because they are less able to evade the electrodes in trying to escape upstream out of the electrified zone.

### Stream Velocity

Galvanotropic screens will probably be effective for guiding yearling salmon only where the water velocity is considerably less than 1.5 feet per second because this velocity is often quoted as being the maximum permissible velocity for screening salmon with mechanical wire screens (Holmes, 1948). In higher velocities the fish would be swept through the electrified zone or would be unable to swim against the current because of the partial impairment of their swimming ability resulting from electrical exposure.

The usual velocity condition in the test flume at the electrodes was an average velocity of 0.34 feet per second, with a maximum velocity of about 0.7 feet per second. On three occasions the water velocity was altered by changing the height of the dam at the downstream end of the flume and by changing the size of the trap entrances. The results of the three comparisons of the effect of water velocity are shown below:

*Electrodes:* 1-inch diameter, 36 inches between rows, 12-inch spacing in each row, 45° angle of deflection.

*Stimulus:* Interrupted direct current, 4 pulses per second, 80 per cent duty cycle, 1.50 volts per inch.

| *Velocity (Feet Per Second)* | | *Guiding Efficiency* |
|---|---|---|
| *Average* | *Maximum* | *(Per cent)* |
| 0.27 | 0.46 | 96.44 |
| 0.68 | 0.89 | 97.95 |

*Electrodes:* 1-inch diameter, 36 inches between rows, 12-inch spacing in each row, 45° angle of deflection.

*Stimulus:* Direct current, 1.50 volts per inch.

| *Velocity (Feet Per Second)* | | *Guiding Efficiency* |
|---|---|---|
| *Average* | *Maximum* | *(Per cent)* |
| 0.27 | 0.46 | 98.42 |
| 0.68 | 0.89 | 97.96 |

*Electrodes:* 1-inch diameter, 48 inches between rows, 12-inch spacing in each row, 45° angle of deflection.

*Stimulus:* Interrupted direct current, 4 pulses per second, 80 per cent duty cycle, 1.0 volts per inch.

| *Velocity (Feet Per Second)* | | *Guiding Efficiency* |
|---|---|---|
| *Average* | *Maximum* | *(Per cent)* |
| 0.21 | 0.32 | 66.14 |
| 0.68 | 0.89 | 83.33 |

The first two pairs of tests were conducted under comparable conditions but in the last pair of tests, the low velocity of 0.21 feet per second was achieved by reducing the size of the trap entrances to one-half their normal size. The low guiding efficiency in this test might be attributable to a disproportionate decrease in efficiency of the traps rather than to the effect of the reduction in water velocity. Observations of the activity of Cultus Lake yearling sockeye indicated that the galvanotropic screen would probably have guided these fish effectively in water velocities higher than those obtainable in these experiments.

### Angle of Deflection

The "angle of deflection" may be defined as the acute angle between the direction of stream flow and the plane of the electrodes. It is also the angle through which fish swimming in the direction of stream flow must turn in order to follow along the row of electrodes to the by-pass. Highest guiding efficiencies

would probably be obtained with galvanotropic screens placed so as to make the smallest possible angle with the direction of stream flow. That is, the efficiency of guiding would probably be highest when the angle through which the fish must be turned is a minimum.

Most of the experiments were conducted with the electrodes forming an angle of 45° with the direction of stream flow, a few with an angle of 60°. None were conducted with an angle of 90° so it is not known whether the efficiencies would have been decreased if the fish had to turn as much as 90° in order to reach the by-pass. The efficiencies obtained with a 60° angle of deflection were somewhat lower than those obtained with 45° but this may not be significant as the electrodes in the two tests were not the same size.

### Polarity

The reaction of fish to galvanotropic screens was dependent on the polarity of the electrodes. It was found that the galvanotactic response could be utilized to attract fish downstream through the electrified area when the downstream row of electrodes was made positive and that it was difficult for the fish to escape upstream through the electrified area again. Previously the anode or positive electrode had been placed at the upstream face of the electrified zone and fish entering this electrified zone were attracted back upstream. However, when the anode was placed at the downstream face of the electrified zone the fish were involuntarily attracted downstream. The data and observations from two pairs of tests in which the effect of polarity reversal was investigated are shown below:

*Electrodes:* Hanging chain, 48 inches between rows, 6-inch spacing in each row, 45° angle of deflection.

*Stimulus:* Interrupted direct current, 4 pulses per second, 80 per cent duty cycle, 1.25 volts per inch.

| *Number of Fish* | *Per cent in By-pass* | *Guiding Efficiency* |
|---|---|---|
| | *Anode Upstream* | |
| 1,409 | 92.76 | 87.83% Repulsion |

*Observations:* Immobilization was severe, galvanotropism was fair. Very few, if any, fish remained in the test area downstream from the electrodes at the end of the test.

| *Number of Fish* | *Per cent in By-pass* | *Guiding Efficiency* |
|---|---|---|
| | *Anode Downstream* | |
| 4,118 | 2.33 | 94.25% Attraction |

*Observations:* Practically no immobilization. Upon entering the electrified zone the fish dispersed immediately and swam downstream very actively towards the anode and out of the electrified zone. An estimated 20,000 to 30,000 fish were downstream from the electrodes at the end of the test.

*Electrodes:* 2½-inch horizontal pipe, 24 inches between rows, 12-inch spacing in each row, 45° angle of deflection.

*Stimulus:* Interrupted direct current, 4 pulses per second, 80 per cent duty cycle, 1.25 volts per inch.

| *Number of Fish* | *Per cent in By-pass* | *Guiding Efficiency* |
|---|---|---|
| | *Anode Upstream* | |
| 1,675 | 99.64 | 99.40% Repulsion |

*Observations:* There was no immobilization, the galvanotropism was fair. Very few, if any, fish remaining in the test area downstream from the electrodes at the end of the test.

| *Number of Fish* | *Per cent in By-pass* | *Guiding Efficiency* |
|---|---|---|
| | *Anode Downstream* | |
| 960 | 1.87 | 95.37% Attraction |

*Observations:* No immobilization. At the end of the test there were no fish upstream from the electrodes but about 10,000 fish downstream from the electrodes.

When the downstream row of electrodes was made positive practically all of the fish that entered the test area were attracted through the electrified zone and accumulated in large numbers downstream from the electrodes. Their rate of movement downstream was increased when passing through the electrified zone and very few of the fish were able to escape upstream again.

It is likely that by-passes and other trapping devices could be made more effective by using reverse-polarity galvanotropic screens.

### Intersecting Fields

Lethlean (1953) reported some success in diverting yearling downstream-migrant Atlantic salmon *(Salmo salar)* with an electric screen that extended across the forebay of the Dunalastair Dam in Scotland. From laboratory experiments Lethlean concluded that the greatest diversion of fish could be obtained when "intersecting" voltages were applied between two parallel rows of electrodes. A special arrangement of electrodes was required. In the Dunalastair installation, the anode or upstream row consisted of 11-inch diameter electrodes 8 feet apart and the downstream row consisted of 2-inch diameter rods 1 foot apart. The distance between the two rows was 6 feet. The cathode row was divided into sections of 8 electrodes each, and each section was placed opposite one of the anode electrodes. When the voltage was first applied, a pulse was produced between the odd-numbered anode electrodes and the even-numbered cathode sections. This pulse was the positive half of a 50-cycle sine wave and had a total duration of about 10 milliseconds. After an "off time" of 10 milliseconds another 10-millisecond positive pulse was produced between the even-numbered anodes

and the odd-numbered cathode sections. There was then a 70-millisecond "off time" before this cycle was repeated. The complete cycle was repeated 10 times every second. In terms of time, the stimulus was 10 per cent on, 10 per cent off, 10 per cent on, then 70 per cent off.

Because of the success reported by Lethlean with this intersecting field arrangement, an attempt was made at Cultus Lake to compare the efficiencies

TABLE 16

SUMMARY OF TESTS OF ELECTRICAL GUIDING IN THE 16-FOOT FLUME USING INTERSECTING FIELDS. INTERRUPTED DIRECT CURRENT, 45° ANGLE OF DEFLECTION.

| *Voltage Gradient v/in.* | *Total No. of Fish* | *Per Cent in By-pass* | *Guiding Efficiency (per cent)* | *Galvanotropism* | *Immobilization* |
|---|---|---|---|---|---|
| *Electrodes:* Upstream row, 3-inch diameter, 48-inch spacing; downstream row, 1-inch diameter, 12-inch spacing; 36-inch distance between rows. | | | | | |
| *Stimulus:* Each cycle 10% on, 50% off, 10% on, 30% off, at a repetition rate of 4 cycles per second. | | | | | |
| 3.33 | 825 | 0.97 | 97.61* | None | None |
| 4.17 | 1,066 | 30.49 | 24.77* | Poor | Slight |
| 5.00 | 754 | 56.10 | 26.12 | Poor | Severe |
| *Stimulus:* Each cycle 10% on, 10% off, 10% on, 70% off, at a repetition rate of 10 cycles per second. | | | | | |
| 2.50 | 805 | 70.31 | 50.10 | Poor | Severe |
| 3.33 | 1,439 | 74.22 | 56.66 | Poor | Severe |
| *Stimulus:* Each cycle 10% on, 10% off, 10% on, 70% off, at a repetition rate of 4 cycles per second. | | | | | |
| 2.00 | 547 | 75.32 | 58.46 | Poor | Slight |
| 2.67 | 2,029 | 79.05 | 64.79 | Poor | Severe |
| 3.33 | 1,822 | 77.11 | 61.50 | Poor | Severe |
| *Electrodes:* 1-inch diameter, 36-inch distance between rows, 12-inch spacing in each row. | | | | | |
| *Stimulus:* Each cycle 10% on, 10% off, 10% on, 70% off, at a repetition rate of 4 cycles per second. | | | | | |
| 2.67 | 885 | 77.06 | 61.41 | Poor | Severe |
| *Electrodes:* 1-inch diameter, 24-inch distance between rows, 12-inch spacing in each row. | | | | | |
| *Stimulus:* Each cycle 10% on, 10% off, 10% on, 70% off, at a repetition rate of 4 cycles per second. | | | | | |
| 1.50 | 1,872 | 21.79 | 46.25* | None | None |
| 3.00 | 1,213 | 33.39 | 17.68* | None | None |
| 5.00 | 773 | 51.62 | 18.52 | Poor | None |
| *Stimulus:* Each cycle 10% on, 10% off, 10% on, 70% off, at a repetition rate of 10 cycles per second. | | | | | |
| 5.00 | 4,275 | 56.73 | 27.22 | Fair | Slight |
| 6.00 | 3,014 | 71.30 | 51.74 | Poor | Severe |

* Fish were attracted instead of being repelled by the electric screen.

obtained using this type of screen with those obtained using the galvanotropic screen. A duplicate of the electrode array used by Lethlean could not be installed because of size limitations in the test area. However, the same general arrangement of electrodes was tried on a smaller scale and intersecting fields were produced at about the same angle as used by Lethlean. Other frequencies, duty cycles and electrode arrangements were also tried. Pulses of interrupted direct current with duty cycles approximately the same as the rectified current pulses previously described were used to energize the electrode array.

Table 16 gives the results of tests that were conducted in the 16-foot flume. All the combinations of electrode arrangement, duty cycle, frequency and voltage gradient that were tried produced much lower guiding efficiencies than those obtained with the galvanotropic screen. One disadvantage of the intersecting fields was that the fish were immobilized in the concentrated field near the anodes and were swept through the electrified area. Furthermore, the very short duration of the pulses did not produce a good galvanotropic response. These results suggested that screens using intersecting fields were considerably less effective than simple galvanotropic screens for diverting yearling sockeye salmon.

### Length of Electrical Screen

In the spring of 1954 several tests were conducted with a galvanotropic screen spanning the full width of Sweltzer Creek to determine if fish could be guided over a long distance with the same efficiency as had been obtained with the shorter screen.

The rows of electrodes in these experiments were 186 feet long, extending from the right bank of Sweltzer Creek to a point on the wire screen fence 16 feet from the left bank and forming an angle of 45° with the general direction of stream flow. Each of the two electrode rows consisted of a single length of hexagonal wire-mesh fencing supported vertically with wooden stakes. The distance between the two rows was 4.0 feet. The size of the meshes in the wire screen was 6 inches by 4 inches and the wire was 1/32-inch diameter galvanized iron. The position of these electrodes is shown in Figure 8. The water depth, measured at 4-foot intervals midway between the two rows averaged 2.5 feet; the minimum depth being 1.9 feet and the maximum 3.6 feet. The average velocity was 0.35 feet per second and the maximum was 0.68 feet per second.

Two traps were installed to catch fish that penetrated the galvanotropic screen, and the 16-foot flume served as the by-pass (Figure 8). Thus, for these tests, both the traps in the flume constituted by-pass traps and the two traps behind the electrodes were the spillway traps. All were inclined-plane wire-screen traps consisting of a subsurface entrance, a length of sloping ¼-inch-mesh wire screen, and a 4- by 8-foot trap enclosure.

Both continuous direct current and interrupted direct current were used but because of the much larger area screened, the power requirements were much higher than in previous experiments and the same rotating switch could not be used to interrupt the direct current. An electronic switching unit was therefore

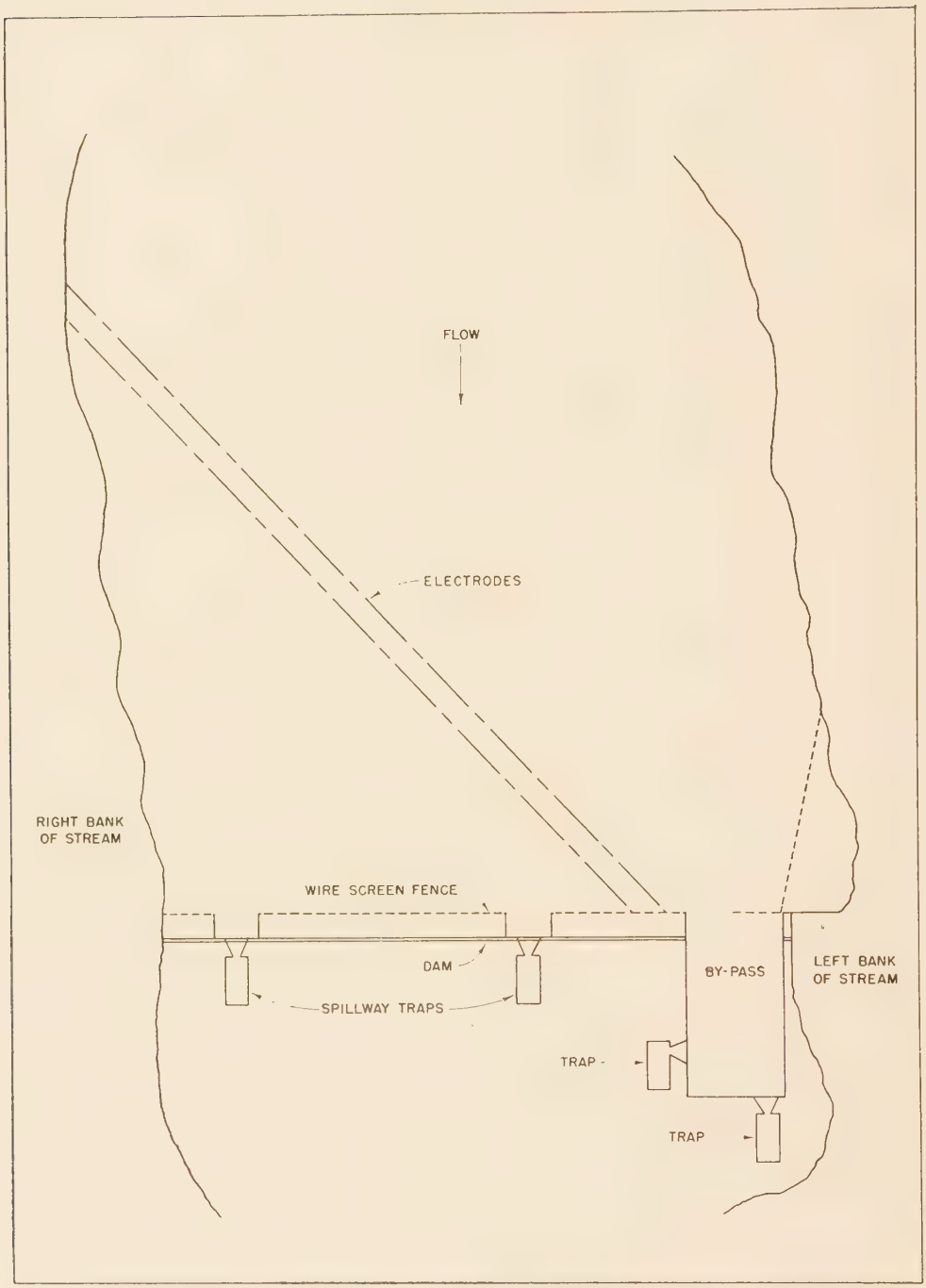


FIGURE 8. Experimental installation used for testing a long galvanotropic screen in Sweltzer Creek, 1954.

used for this purpose. In this electronic circuit an ignitron was used to conduct current from a 5-kilowatt direct-current generator to the electrodes. The discharge of a condenser initiated current flow in the ignitron and the current flow was stopped by passing the discharge of another condenser through the ignitron in the opposite direction to the original current flow. The condensers were discharged through thyratrons and the timing of the discharges of these condensers controlled the duty cycle and frequency of the interrupted direct current. A mechanical rotating switch was used to bias the thyratron grids and thus to control the timing of the condenser discharges. Currents as high as 35 amperes were controlled with this electronic circuit.

Before beginning a test or a control, it was necessary to scare upstream all fish that had accumulated in the test flume and the area downstream from the electrodes. This could be done during daylight by splashing the water surface for 5 or 10 minutes but since it was not possible to scare all the fish upstream during darkness, tests could be conducted only during daylight. After all the fish had been scared upstream the electrodes were energized and when several thousand fish had been caught in the traps the entrances were simultaneously closed and the fish counted in the manner previously described for the flume experiments.

In a preliminary test conducted on May 1, the electrodes were energized with 48 volts of direct current and observations were made of the behavior of the fish. Practically all of the fish were stopped by the electric screen but only a small proportion entered the by-pass. The fish that were repelled usually travelled along the upstream side of the anode but, at times, small groups of fish were seen swimming through the electrified zone in both directions. After the fence had been electrified for a short time schools were seen in an almost continuous line parallel to and about 15 feet upstream from the anode row. Only a few schools remained immediately upstream from the anode. Although nearly all the fish were repelled upstream, very few entered the flume to the by-pass traps. The entrance to this flume was located immediately adjacent to the downstream end of the anode. It was 8 feet wide and the water was 2 feet deep, moving at an average velocity of 0.6 feet per second. Fish near this opening exhibited some distress, probably caused by a slight electrical shock from the stray field at the end of the anode, and consequently they did not readily enter the by-pass. Frequently, they attempted to swim through the electrified area about 12 feet from the by-pass. Thus, although at the upstream end of the electric screen all the schools moved *downstream* along the face of the anode, the movement along the electrodes near the by-pass was *upstream*. The fish usually did not approach closer than about 2 feet to the by-pass but fish at the trailing edge of a school were occasionally swept through the by-pass opening. A few minutes after the power was shut off, thousands of fish swam through the electrodes and then back and forth along the fence without avoiding the non-energized electrodes. It was concluded that the galvanotropic screen was effective in stopping the fish but that the by-pass opening should have been located farther away from the electrodes to ensure that the fish would have had sufficient space to congregate at the entrance without being startled or distressed.

Since time did not permit moving the electrodes away from the by-pass, an additional wire screen fence (Figure 8) was built along the left bank in an effort to lead the fish to the by-pass opening. This lead, built of panels of ¼-inch-mesh wire screen, extended 32 feet upstream from the existing wire screen fence. Although the fish still received a slight shock immediately upstream from the by-pass, this additional fence was partially successful in leading them to the by-pass opening.

TABLE 17

GUIDING EFFICIENCIES OBTAINED WITH A 186-FOOT LONG GALVANOTROPIC SCREEN IN SWELTZER CREEK DURING DAYLIGHT.

*Electrodes:* 1/32-inch diameter wire screen, mesh size 6 inches by 4 inches, 48 inches between electrode rows, 45° angle of deflection.

| *Time* | | *Voltage Gradient (v/in.)* | *Total No. of Fish* | *Per cent in By-pass Traps* | *Guiding Efficiency (per cent)* |
|---|---|---|---|---|---|
| *Start* | *End* | | | | |
| May 3 *Direct current* | | | | | |
| 6:20 p.m. | 6:40 p.m. | 1.25 | 5,898 | 95.41 | 94.25 |
| 6:56 p.m. | 7:16 p.m. | Control | 8,867 | 31.21 | |
| 7:35 p.m. | 7:55 p.m. | 1.25 | 9,001 | 96.00 | 94.99 |
| 8:08 p.m. | 8:28 p.m. | Control | 23,582 | 16.00 | |
| May 6 *Interrupted direct current, 4 pps, 80% duty cycle* | | | | | |
| 6:20 p.m. | 6:50 p.m. | 1.50* | 1,143 | 98.34 | 97.92 |
| 7:03 p.m. | 7:18 p.m. | Control | 6,333 | 19.75 | |

* This voltage gradient was too high; some fish were killed near the electrodes.

The results of the tests conducted during daylight after this lead had been installed are shown in Table 17. The guiding efficiencies were calculated using the average of the three measured control distributions in the manner previously described. The guiding efficiencies obtained in the large-scale tests were about the same as those obtained in the small-scale tests shown in Table 9 even though the large electrical screen was almost 8.5 times as long as that used in the small-scale tests. Although no conclusions could be made regarding the efficiency of a large-scale galvanotropic screen during periods of darkness, it was noted that the experiments conducted in the 16-foot flume did not reveal any decrease in guiding efficiency during darkness. It was concluded, however, that during daylight downstream-migrant sockeye would be guided for considerable distances along a galvanotropic screen in clear, shallow water.

### Other Factors

There are a number of other factors that probably affect the efficiency of galvanotropic screens. One of these is the schooling behavior of the fish. Sockeye salmon fingerlings invariably migrate in schools, the behavior of a large number of fish being controlled by the reaction of relatively few. In the experiments it was observed that nearly all the sockeye in each school were guided

upstream by the galvanotropic screen as a result of only one or two fish in the school venturing into the electrified area and quickly retreating upstream. Furthermore, when a few fish from a school escaped downstream through the electrified zone they usually passed upstream again to rejoin the major part of the school. It is not known whether their behavior would have been the same in turbid water. It is possible that high guiding efficiencies might not have been obtained in turbid water or with other species that do not exhibit schooling behavior to the same extent as sockeye.

Temperature may also influence the effectiveness of galvanotropic screens, not only because of its effect on activity of the fish but also because of its effect on water resistivity. The variations in temperature and resistance of Sweltzer Creek water during these experiments was so slight that the guiding efficiency was not noticeably changed. Laboratory experiments mentioned earlier, however, showed that as the resistivity was increased the galvanotropic response became less pronounced. If a galvanotropic screen were installed at a location where the water resistivity was quite variable it is likely that the guiding efficiency would also vary unless changes in resistivity could be continually compensated for by adjusting the intensity of the stimulus. A galvanotropic screen would not be expected to operate as effectively in water of high resistivity as in an area where the resistivity was low.

## TESTS OF A PROTOTYPE ELECTRIC FISH SCREEN

An experiment was conducted in the spring of 1955 to measure the effectiveness of an electric screen placed across the forebay at the Baker River hydroelectric plant of the Puget Sound Power and Light Company at Concrete, Washington. The previously described experiments indicated that galvanotropic stimuli would be far more effective than other artificial stimuli for guiding downstream-migrant sockeye salmon. Before this method could be used in practice, however, it was necessary to measure the guiding efficiency that could be obtained with prototype electric fish screens and to investigate the practical problems involved in their operation.

A galvanotropic screen was installed upstream from the spillway and the turbine intake to divert fish to a by-pass trap at the crest of the dam. Nets and traps were installed below the dam and a sampling procedure was used to calculate the number of fish that passed over the spillway and through the tunnel. The effectiveness of the electric screen was then determined by comparing the catches in the by-pass trap with the computed spillway and turbine escapements.

### Description of the Hydroelectric Plant

The Baker River plant, situated on the Baker River one mile above its confluence with the Skagit River in the northwestern part of the State of Washington, produces a maximum of about 54,000 horsepower operating at a head of 250 feet and a discharge of 2200 cubic feet per second. The reservoir created by the dam is about nine and a half miles long and has a maximum depth of 240 feet. At the face of the dam the maximum depth is about 220 feet. The water for power

generation is taken from the 85- to 107-foot levels below full reservoir elevation and is carried in a 22-foot diameter tunnel to the powerhouse, about 1200 feet downstream. Surplus water is spilled over the crest of the dam through vertical lift gates 9 feet 6 inches wide by 13 feet high, each having a maximum discharge capacity of about 1700 cubic feet per second.

FIGURE 9. Downstream face of Baker Dam, showing 24 cfs discharge from the by-pass trap on the extreme left, and 24 cfs discharge from the spillway trap and 1500 cfs discharge from an open spillway gate downstream from the electric screen.

The average annual run of adult salmon in the Baker River consists of about 3,000 sockeye and 10,000 coho. Provision has been made for trapping these fish by means of a weir extending across the river at the powerhouse and for transporting them over the dam in a tank carried on an aerial cableway but no provision has been made to ensure safe passage for downstream migrants.

### Description of Experimental Facilities

The design of the electric screen used at Baker Dam was based on the results of the experiments conducted in Sweltzer Creek, where guiding efficiencies greater than 90 per cent had been achieved, and on previous observations of the behavior of downstream migrants in the forebay of Baker Dam.

It was considered unnecessary as well as impractical to extend the electrodes to the full 220-foot depth of the forebay. Recent experiments had shown that over 95 per cent of the downstream-migrant sockeye and coho salmon used the surface spillway as an exit from the forebay and that less than 5 per cent used the tunnel exit (Hamilton and Andrew, 1954). Since previous observations showed that a large proportion of the downstream-migrant salmon arriving at Baker Dam were near the surface of the forebay and since the electrodes were located close to the surface spillway exit, it was decided that practically all of the fish would encounter the electric screen in their normal migration if the electrodes extended from the surface to a depth of 50 feet.

The screen consisted of vertical electrodes in two parallel rows spaced two feet apart, extending from a point on the east shore of the forebay to about the center of the spillway section of the dam, a distance of 252 feet. In each row, electrodes were hung vertically one foot apart on a single length of ¼-inch diameter bare copper wire supported by cork floats. Cedar blocks used to space the electrode rows also provided additional buoyancy. Two electrode materials were tried, the first of aluminum and the second of iron. The first electrode installation was made from 10-foot lengths of ⅛-inch diameter aluminum wire, five lengths being hooked end-to-end to extend to the required depth. The top ends of the electrodes were wound tightly around the ¼-inch diameter copper wires at the water surface. These aluminum electrodes proved to be unsatisfactory because of electrolytic corrosion and were later replaced by galvanized iron wire of the same diameter. The iron electrodes were installed in 50-foot lengths instead of in series of 10-foot lengths.

The electric screen was energized with direct current from a motor-generator unit located on the east shore of the forebay about 250 feet upstream from the dam. Although the previous experiments at Cultus Lake indicated that interrupted direct current might have been preferable, no means were available for producing interrupted direct current of the magnitude required at this prototype installation. The direct-current generator was a 75-kilowatt, 120-volt, 625-ampere stabilized shunt-wound machine driven by a 115-horsepower, 440-volt, 3-phase, 60-cycle, squirrel-cage induction motor. The output voltage of the generator was controlled by a shunt-field rheostat located in a control panel which also contained an air circuit breaker and a bus structure. From this direct current bus, four sets of feeder lines were taken to selected points on the copper wires supporting the electrodes. The four sets of feeders were used in order to minimize voltage differences along the wires supporting the electrodes. Three meters located on the control panel measured bus voltage, total generated current and the currents in each of the outgoing feeders.

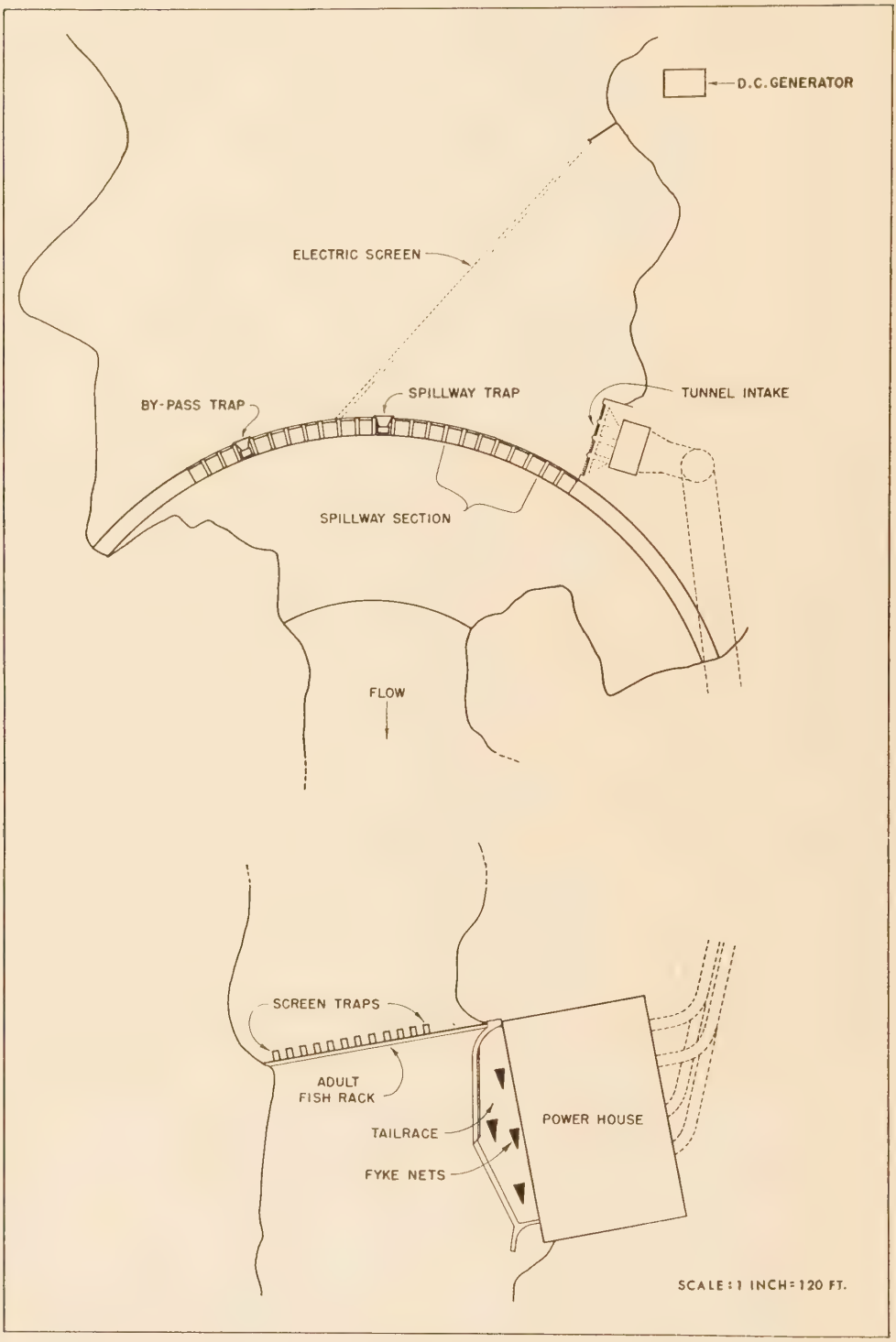


FIGURE 10. Experimental facilities at Baker Dam, 1955.

The by-pass, consisting of an adjustable inclined-plane wire-screen trap, was constructed on the downstream side of spillway gate number four located near the west shore of the forebay (Figure 10). The entrance to the trap was an orifice 6 inches by 7 feet 3 inches, with the long axis horizontal and the top of the orifice submerged 20 inches below the water surface. An inclined, ¼-inch-mesh wire screen 6 feet long extended from the bottom of this orifice to a plywood live box, 5 feet long, 4 feet wide and 1.5 feet deep. Most of the water passing through the orifice dropped through the inclined screen while the remainder passed over the screen in a thin layer and swept the fish into the live box from which they could not escape. The spillway gate, orifice, inclined screen, live box and a working platform could be raised or lowered as a unit by means of a spillway gate hoist so that a constant head could be maintained on the orifice despite fluctuations in reservoir elevation. The orifice discharged 24 cubic feet of water per second, the theoretical velocity through the orifice being 11.1 feet per second.

FIGURE 11. Forebay of Baker Dam, showing the electric screen.

A "spillway" trap identical to the by-pass trap was constructed near the center of the dam, downstream from the electric screen, at spillway gate number 12. Its purpose was to catch fish that escaped through the electric screen during periods when there was no discharge over the spillway. Although the by-pass trap was modified on numerous occasions in an effort to make it more efficient, the spillway trap remained unchanged throughout the experimental period.

To enumerate the migration over the spillway, 12 screen traps were placed on the inclined upstream face of an adult fish rack located in the river below the

spillway and immediately upstream from the discharge of the turbines. Each trap consisted of a rectangular box 4 feet wide, 8 feet long and 8 inches deep with a ¼-inch-mesh wire screen bottom and wooden sides. These traps were supported on casters which ran in guides on the face of the fish rack.

To determine the migration through the tunnel and turbines four webbing fyke nets were located in the tailrace of the power plant. Two of these nets were 6 feet square at the upstream end and the other two were 5 feet square.

The efficiency of the respective enumeration gears was determined by measuring the rates of recovery of known numbers of marked native sockeye and coho and hatchery-reared spring salmon (*O. tschawytscha*) released over the spillway and through the tunnel. Marking was done with an electric tattooing machine. Fish were released over the spillway by pouring small groups of fish from a bucket into the fast-flowing water immediately upstream from the open spillway gates. Releases into the tunnel were made by lowering groups of fish in a weighted bag down an air vent near the upstream end of the tunnel. The bag consisted of a 30-inch-square piece of cloth with one corner securely tied to a lowering rope. The other three corners were gathered up to surround a group of fish and then tied to the rope by a thin thread. After the bag had been lowered 90 feet to the high-velocity water flowing in the tunnel, the fish were released by a sharp upward pull on the rope, which broke the tying thread.

### Computation of Migration Rates

The number of fish released and the number of each group recovered are shown in Tables 18 and 19. Releases of sockeye and coho over the spillway were made at the one-, two-, and three-gate spill conditions but releases of springs were made at the one-gate spill condition only. The recovery rate of coho at one gate of spill was much lower than that for the other species. Apparently the low velocities at the entrances of the traps in the river below the dam allowed some of the coho to escape during a one-gate spill but the sockeye and springs, being smaller than the coho, were retained. With two and three gates spilling, the velocities at the traps were higher and it is believed that none of the fish were able to escape. The variations in the recovery rates were analyzed using Fisher's "F" values at the 5 per cent level to determine whether there were significant differences between the recovery rates for the different species and for different spillway discharges. Comparing species, it was found that with one gate spilling the recovery rates of sockeye and springs were not significantly different but that these rates were significantly different from those of coho; when more than one gate was spilling there was no significant difference between the recovery rates for sockeye and coho. Similarly, comparing the effect of different spillway discharges, there was no significant difference between the combined recovery rates of sockeye and springs at the one-gate spill condition and the combined recovery rates of sockeye and coho when more than one gate was spilling.

The variations in the recovery rates in the tailrace were also analyzed and it was determined that there was no significant difference at the 5 per cent level between the rates of recovery of sockeye, coho and spring salmon.

TABLE 18

RECOVERY RATES OF MARKED FISH RELEASED OVER THE SPILLWAY.

| *Number of Spillway Gates Open* | *Species* | *Number Released* | *Number Recovered* | *Per cent Recovered* |
|---|---|---|---|---|
| *Low Recovery Rate* | | | | |
| 1 | Coho | 375 | 9 | 2.40 |
| | | 489 | 8 | 1.64 |
| | | 1,124 | 25 | 2.22 |
| | Unweighted average | | | 2.09 |
| | Weighted average | | | 2.11 |
| *High Recovery Rate* | | | | |
| 1 | Sockeye | 100 | 6 | 6.00 |
| | | 58 | 5 | 8.62 |
| | | 119 | 13 | 10.92 |
| | Spring | 1,002 | 75 | 7.49 |
| | | 907 | 69 | 7.61 |
| | | 1,187 | 134 | 11.29 |
| | | 562 | 66 | 11.74 |
| | | 274 | 36 | 13.14 |
| 2 | Sockeye | 82 | 5 | 6.10 |
| | Coho | 919 | 59 | 6.42 |
| 3 | Sockeye | 27 | 1 | 3.70 |
| | | 111 | 3 | 2.70 |
| | | 72 | 9 | 12.50 |
| | Coho | 205 | 18 | 8.78 |
| | | 208 | 13 | 6.25 |
| | | 397 | 16 | 4.03 |
| | | 904 | 59 | 6.53 |
| | Unweighted average | | | 7.87 |
| | Weighted average | | | 8.23 |

TABLE 19

RECOVERY RATES OF MARKED FISH RELEASED THROUGH THE TUNNEL.

| *Species* | *Number Released* | *Number Recovered* | *Per cent Recovered* |
|---|---|---|---|
| Sockeye | 73 | 15 | 20.55 |
| | 142 | 16 | 11.27 |
| Coho | 853 | 166 | 19.46 |
| | 841 | 162 | 19.26 |
| Spring | 726 | 179 | 24.65 |
| | 363 | 77 | 21.21 |
| | 273 | 45 | 16.48 |
| | 1,011 | 247 | 24.43 |
| Unweighted average | | | 19.66 |
| Weighted average | | | 21.18 |

Although the recovery rates compared in the analyses of variance were of course unweighted, similar rates were weighted by the numbers in the samples to obtain the most representative overall recovery rates for use in subsequent enumeration calculations. The 95 per cent confidence limits for similar unweighted recovery rates were computed in the manner previously described and were as follows:

Coho, one gate spilling $= 2.09 \pm 0.99$ per cent

Sockeye and springs, one gate spilling and sockeye and coho, more than one gate spilling $= 7.87 \pm 1.62$ per cent

Sockeye, coho and springs in the tailrace $= 19.66 \pm 3.63$ per cent

The weighted mean recovery rates for these conditions were 2.11, 8.23 and 21.18 per cent respectively.

Fish were removed from the screen traps and from the fyke nets at frequent intervals, usually every two hours. Knowing the number of fish captured and the mean recovery rate it was possible to compute the migration during any fishing period. The estimated numbers of fish migrating past the dam during the experimental period from April 17 to June 24, are shown in Table 20. Although the migration commenced before April 17 and had not ended on June 24, the main sockeye migration (daily migration exceeding 500 fish) extended from May 9 to June 13 inclusive, with an estimated peak of 21,000 fish on May 19. The migration of coho exceeded 500 fish daily between May 9 and June 23 inclusive and the peak occurred on May 20 with an estimated migration of 9,000.

TABLE 20

ESTIMATED MIGRATION OF YEARLING SOCKEYE AND COHO AT BAKER DAM, APRIL 17 TO JUNE 24, 1955.

| | *SOCKEYE* | | | | *COHO* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Number* | *Per Cent* | *95% Confidence Limits* | | *Number* | *Per Cent* | *95% Confidence Limits* | |
| | | | *Upper* | *Lower* | | | *Upper* | *Lower* |
| Spillway | 77,229 | 80.95 | 96,150 | 64,525 | 68,120 | 72.20 | 106,302 | 51,703 |
| Tunnel | 11,850 | 12.42 | 14,300 | 10,116 | 7,919 | 8.39 | 9,557 | 6,760 |
| By-pass Trap | 5,737 | 6.01 | | | 16,536 | 17.53 | | |
| Spillway Trap | 587 | 0.62 | | | 1,770 | 1.88 | | |
| Total | 95,403 | 100.00 | 116,774 | 80,965 | 94,345 | 100.00 | 134,165 | 76,769 |

### Efficiency of Electric Screen

Many tests were conducted during daylight and darkness to test the effectiveness of the galvanotropic screen at different voltage gradients. Tables 21 and 22 show the combined data. The catches in the by-pass trap, in the spillway trap and the estimated escapements over the spillway and through the tunnel are shown as percentages of the total number of fish migrating from the reservoir during each set of experimental conditions. During the no-spill condition most of the sockeye

TABLE 21

CONTROL AND TEST DISTRIBUTIONS OF SOCKEYE UNDER VARIOUS EXPERIMENTAL CONDITIONS.

| *Voltage on Electrodes* | *DAYLIGHT* | | | | | *DARKNESS* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10* | 30* | 48 | 60 | 0 | 10* | 30* | 48 | 60 |
| | (Control) | | | | | (Control) | | | | |
| | | | | | *No Spill* | | | | | |
| No. of Tests | 24 | 5 | | 3 | 2 | 15 | 3 | | 1 | 1 |
| No. of Fish | 1,112 | 235 | | 43 | 48 | 5,898 | 1,068 | | 113 | 144 |
| % Through Tunnel | 94.69 | 98.30 | | 100.00 | 91.67 | 60.68 | 54.03 | | 30.09 | 76.39 |
| % in Spillway Trap | 4.23 | 1.70 | | 0 | 0 | 6.92 | 1.78 | | 0 | 0.69 |
| % in By-pass Trap | 1.08 | 0 | | 0 | 8.33 | 32.40 | 44.19 | | 69.91 | 22.92 |
| | | | | | *One-Gate Spill* | | | | | |
| No. of Tests | 9 | 2 | | 10 | 4 | 7 | 1 | | 6 | 1 |
| No. of Fish | 3,668 | 8,324 | | 1,409 | 94 | 1,758 | 5,121 | | 2,523 | 261 |
| % Through Tunnel | 3.22 | 5.64 | | 17.53 | 41.49 | 9.10 | 28.59 | | 29.92 | 33.72 |
| % Over Spillway | 96.65 | 94.29 | | 81.76 | 56.38 | 87.03 | 67.62 | | 63.10 | 63.98 |
| % in Spillway Trap | 0 | 0.02 | | 0.07 | 2.13 | 0 | 0.04 | | 0.04 | 0 |
| % in By-pass Trap | 0.13 | 0.05 | | 0.64 | 0 | 3.87 | 3.75 | | 6.94 | 2.30 |
| | | | | | *Two-Gate Spill* | | | | | |
| No. of Tests | 5 | | | 3 | 4 | 4 | | | 2 | 4 |
| No. of Fish | 4,356 | | | 1,737 | 759 | 2,850 | | | 1,259 | 3,354 |
| % Through Tunnel | 3.49 | | | 2.65 | 21.21 | 4.60 | | | 4.77 | 26.27 |
| % Over Spillway | 95.73 | | | 97.29 | 78.79 | 95.19 | | | 91.10 | 69.44 |
| % in Spillway Trap | 0.05 | | | 0.06 | 0 | 0.04 | | | 0 | 0.03 |
| % in By-pass Trap | 0.73 | | | 0 | 0 | 0.17 | | | 4.13 | 4.26 |
| | | | | | *Three-Gate Spill* | | | | | |
| No. of Tests | 3 | | 1 | | | 3 | | 3 | | |
| No. of Fish | 21,604 | | 602 | | | 12,310 | | 6,039 | | |
| % Through Tunnel | 2.04 | | 9.63 | | | 2.77 | | 6.32 | | |
| % Over Spillway | 97.54 | | 90.37 | | | 96.99 | | 91.79 | | |
| % in Spillway Trap | 0.01 | | 0 | | | 0.01 | | 0 | | |
| % in By-pass Trap | 0.41 | | 0 | | | 0.23 | | 1.89 | | |

*Aluminum electrodes

used the tunnel as an exit from the forebay regardless of the voltage on the electrodes. An exception occurred during darkness when the electrodes were energized with 48 volts but when the voltage was increased to 60, the percentage of the sockeye using the tunnel was higher than in the control. Possibly this was caused by immobilization of the fish in the electrified zone. When one, two or three gates were spilling, most of the fish used the spillway as an exit from the forebay regardless of whether the electrodes were energized or not. In general, the percentage of fish escaping over the spillway decreased as the voltage of the electrodes was increased but most of the fish that were diverted from the spillway exit escaped through the tunnel. The slight increases in the numbers of sockeye entering the by-pass trap during power-on periods were not of practical significance.

The coho appeared to remain in the surface layers of the forebay to a greater extent (Table 22) than the sockeye but no other marked differences in behavior were observed. The percentage of coho using the tunnel was usually lower than the percentage of sockeye but there was the same tendency for the percentage using the tunnel to increase when the electrodes were energized. The percentage of coho passing over the spillway decreased considerably when the electrodes were energized but as the diverted fish sounded and entered the tunnel only a small percentage was captured in the by-pass trap.

The relative proportions of sockeye and coho using the various exits during times when the spillway exit was available is shown graphically in Figure 12. It is evident that neither sockeye nor coho used the by-pass during periods of daylight. The percentage of sockeye using the by-pass during darkness was very low but the percentage of coho was slightly greater. The tendency for the percentage of fish using the spillway to decrease and the percentage using the tunnel to increase when the electrodes were energized is clearly evident in the figure.

On three nights the electrodes were energized during alternate two-hour periods in order to compare the distributions of fish among the various exits during power-on and power-off periods. These comparisons, however, were subject to some error. One source of error was the unavoidable delay between the time the fish entered the forebay downstream from the electric screen and the time when they were taken from the enumeration gear below the dam. To measure the period of delay from the dam to the traps a special test was conducted: At 8:00 p.m. on May 25, 119 sockeye and 1,124 coho were released at the crest of the dam and the screen traps were examined more frequently than usual. Of the sockeye recovered, 70 per cent were caught within 31 minutes after release and the remainder within 12 hours and of the coho recovered, 80 per cent were captured within 31 minutes and the remainder within 3 hours. Although a similar test was not carried out to measure the delay in passage through the tunnel, it was observed that a small proportion of the fish delayed for several days in side passages of the tunnel—the air vents and the surge tower. In addition, there was probably an appreciable delay from the time the fish reached the dam to the time they migrated over the spillway or through the tunnel. Another factor that had to be considered was the constantly changing number of fish available in the forebay. Therefore, the individual rates of migration over the spillway or through the tunnel could not be compared in

TABLE 22

CONTROL AND TEST DISTRIBUTIONS OF COHO UNDER VARIOUS EXPERIMENTAL CONDITIONS.

| *Voltage on Electrodes* | *DAYLIGHT* | | | | | *DARKNESS* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 (Control) | 10* | 30* | 48 | 60 | 0 (Control) | 10* | 30* | 48 | 60 |
| | | | | | *No Spill* | | | | | |
| No. of Tests | 24 | 9 | 2 | | 2 | 21 | 6 | 2 | 3 | 1 |
| No. of Fish | 710 | 350 | 23 | | 68 | 7,864 | 1,157 | 98 | 476 | 513 |
| % Through Tunnel | 79.86 | 76.29 | 82.60 | | 60.29 | 13.81 | 67.07 | 86.74 | 7.98 | 24.17 |
| % in Spillway Trap | 9.86 | 22.00 | 8.70 | | 1.47 | 11.74 | 4.41 | 6.12 | 2.31 | 1.56 |
| % in By-pass Trap | 10.28 | 1.71 | 8.70 | | 38.24 | 74.45 | 28.52 | 7.14 | 89.71 | 74.27 |
| | | | | | *One-Gate Spill* | | | | | |
| No. of Tests | 10 | 2 | | 8 | 6 | 9 | 1 | | 9 | 4 |
| No. of Fish | 7,936 | 6,352 | | 2,238 | 676 | 4,746 | 2,528 | | 9,352 | 1,758 |
| % Through Tunnel | 0.73 | 0.86 | | 7.15 | 7.40 | 2.70 | 9.93 | | 14.02 | 8.13 |
| % Over Spillway | 99.23 | 98.93 | | 91.24 | 91.57 | 87.97 | 83.23 | | 60.49 | 74.12 |
| % in Spillway Trap | 0.01 | 0.13 | | 0.76 | 0.59 | 0.31 | 0.08 | | 0.15 | 0.23 |
| % in By-pass Trap | 0.03 | 0.08 | | 0.85 | 0.44 | 9.02 | 6.76 | | 25.34 | 17.52 |
| | | | | | *Two-Gate Spill* | | | | | |
| No. of Tests | 6 | | | 3 | 4 | 5 | | | 2 | 5 |
| No. of Fish | 4,013 | | | 1,991 | 438 | 2,647 | | | 2,028 | 3,371 |
| % Through Tunnel | 1.20 | | | 0.80 | 15.29 | 1.63 | | | 5.77 | 18.39 |
| % Over Spillway | 98.50 | | | 99.05 | 84.02 | 87.53 | | | 69.62 | 41.80 |
| % in Spillway Trap | 0.15 | | | 0.05 | 0.23 | 1.02 | | | 0.15 | 0.30 |
| % in By-pass Trap | 0.15 | | | 0.10 | 0.46 | 9.82 | | | 24.46 | 39.51 |
| | | | | | *Three-Gate Spill* | | | | | |
| No. of Tests | 3 | | 1 | | | 3 | | 2 | | |
| No. of Fish | 9,387 | | 125 | | | 5,645 | | 1,780 | | |
| % Through Tunnel | 4.53 | | 10.40 | | | 3.53 | | 11.97 | | |
| % Over Spillway | 93.83 | | 88.80 | | | 91.76 | | 61.35 | | |
| % in Spillway Trap | 0.16 | | 0.80 | | | 0.16 | | 0 | | |
| % in By-pass Trap | 1.48 | | 0 | | | 4.55 | | 26.68 | | |

*Aluminum Electrodes

adjacent power-on and power-off periods but it was possible to compare the *relation* between the rate of migration over the spillway and the rate of migration through the tunnel in adjacent periods.

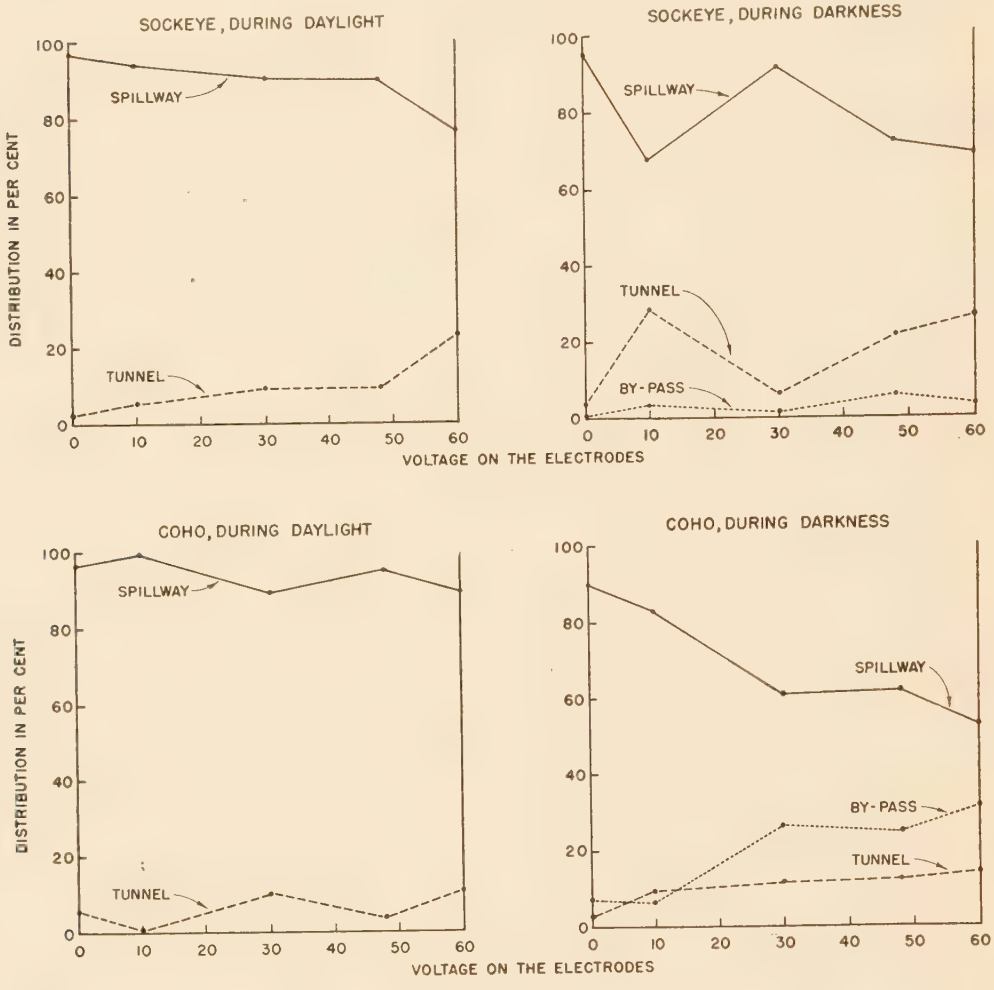


FIGURE 12. Percentage distribution of sockeye and coho over the spillway, through the tunnel, and in the by-pass trap during spillway discharges of one, two and three gates.

The results of the power-on, power-off tests, given in Figure 13, show that when the electrodes were energized there was a reduction in the proportion of fish passing over the spillway and a significant increase in the proportion passing through the tunnel. The greater part of the spillway migration, 61 per cent, occurred when the power was off whereas only 34 per cent of the tunnel migration occurred during power-off periods. The number of fish entering the by-pass remained practically unchanged. It should be noted that because of the previously described delay from time of migration past the electric screen to time of capture in the enumeration gears the measured differences in the proportions passing over

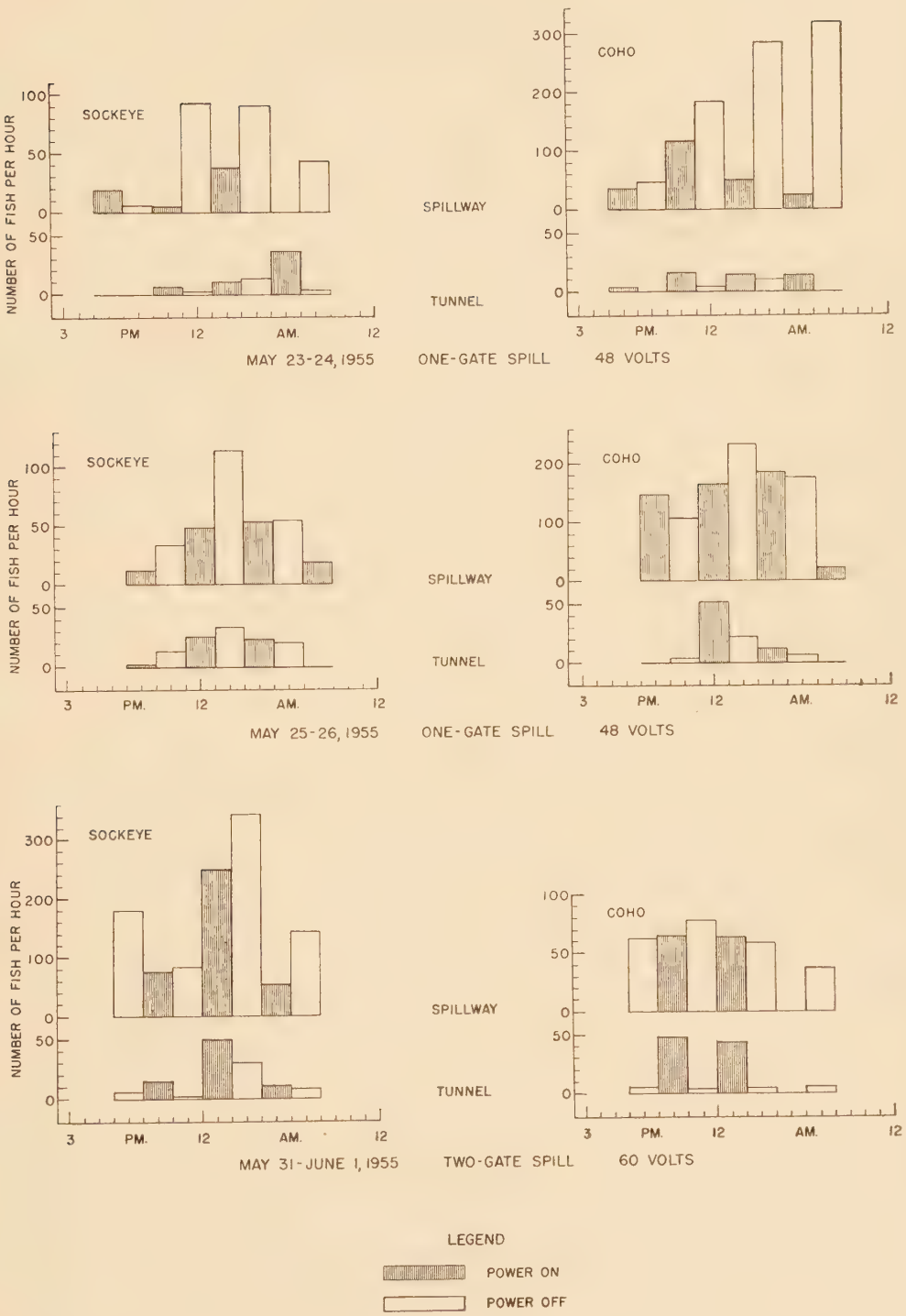


FIGURE 13. Number of sockeye and coho passing over the spillway and through the tunnel per hour when the electrodes were energized for alternate two-hour periods.

the spillway and through the tunnel between power-on and power-off conditions are probably considerably smaller than the actual values. It is indicated that the electric screen did prevent a number of fish from passing over the spillway, at least for a short period of time, but those that were diverted either remained in the forebay or entered the tunnel instead of following along the screen to the by-pass exit.

Observations of the activity of the migrants in the forebay indicated that the fish were not guided along the upstream face of the electric screen in the manner that had been demonstrated in the experiments in Sweltzer Creek. On several occasions large schools of fish were seen approaching the electrodes and were observed to retreat 100 feet or more upstream after they encountered the electrified area. Fish seemed to congregate along the west shore of the forebay but schools were also observed moving downstream in the central area of the forebay. The latter seemed to encounter the electric screen at about the center of the electrode array. Usually their swimming direction was about perpendicular to the electric screen and when the foremost fish in the school entered the electrified area a large part of the school retreated upstream, again swimming in a direction approximately perpendicular to the electric screen. It seemed that many of the fish were being stopped by the electric screen at least near the water surface but that the diverted fish did not follow along the electrified area to the by-pass trap.

Previous experiments had shown that the voltage gradient required to produce galvanotaxis increases as the resistivity of the water increases and decreases as the length of the fish increases. The two species at Baker Dam in 1955 differed distinctly in size, the coho being larger than the sockeye. The mean fork length of sockeye was 3.34 inches with a range of 2.91 to 4.25 inches which was very similar to the mean of 3.31 inches and a range of 2.44 to 4.01 inches found for the sockeye at Cultus Lake in 1954. The mean length of coho was 3.78 inches with a range of 2.68 to 6.30 inches. The specific resistance of the water at Baker was three times that at Cultus, being 10,800 ohms per inch-cube as against 3,360. At Cultus, excellent guiding efficiencies were obtained using 40 volts with the electrode rows spaced two feet apart. Higher voltages were also effective but immobilization became more severe as the voltage was increased. At Baker, voltages from 10 to 60 were tried and it was found that at 48 volts the percentage migration into the by-pass was greater than at 60 volts, indicating that deflection from the screen was greater at 48 volts than at 60. Percentage migration through the tunnel, on the other hand, was less at 48 volts than at 60 volts and it was thought that some of the fish, having been stunned in the electrified zone at the higher voltage, at first settled towards the bottom but recovered later and migrated through the tunnel. It was considered unlikely that a higher voltage would have increased the efficiency of the electric screen as many fish would probably have been stunned and possibly killed.

### Problems Encountered

This study indicated that guiding downstream-migrant salmon with electric screens at an actual installation introduces many problems not encountered in small-scale experiments.

The first problem encountered was electrolytic corrosion of the aluminum electrodes. Corrosion increased the resistance between the two rows of electrodes and therefore decreased the current. When the electrodes were energized with 48 volts, the current decreased 50 per cent in only three hours. To maintain the current at a fixed level the voltage had to be increased continually and the maximum voltage rating of the generator was reached very quickly. It was therefore necessary to maintain the current and the effective voltage at very low levels. Examination of the electrodes when they were removed after being energized at low voltages for 229 hours revealed that the anodes were coated with a grey substance and that the aluminum had become badly pitted and was soft and spongy. The cathodes were covered with a thick deposit of hydroxides that offered a very high electrical resistance. Deposition was particularly severe at the joints between adjacent 10-foot sections of each electrode; the diameter of the cathode wires had almost doubled with the addition of the deposit. Experiments were then conducted to determine the effect of electrolysis on several common metals and it was found that although corrosion could not be eliminated, a non-conductive deposit did not form on iron electrodes. The ⅛-inch diameter iron electrodes that were used to replace the original aluminum electrodes in the electric screen were energized for a total of 315 hours. The resistance between the two electrode rows changed very little during this period but the anodes had become very severely pitted and would have had to be replaced if the experiments had not been terminated. The galvanized iron wires in the cathode row appeared to be unaffected. No practical method is known for eliminating electrolytic corrosion of anode electrodes in water.

The foremost problem was that of guiding the fish along the electrode array to the by-pass exit rather than merely stopping them temporarily; at Baker Dam the electric screen deterred the downstream migrants but did not direct them towards the by-pass. Another requirement was the provision of an effective by-pass that the fish would enter without delay. Although the fish did not appear to be guided towards the by-pass in these tests, many normally migrated downstream along the west shore of the reservoir and accumulated in an area immediately upstream from the by-pass. During daylight schools of several thousand fish, following in the shaded area along the west shore of the forebay and adjacent to the upstream face of the dam, swam within three feet of the submerged orifice leading to the by-pass trap and often remained in the area immediately upstream from the by-pass entrance for long periods of time—perhaps as much as an hour or more. The fish closest to the trap entrance frequently moved to within six inches of the orifice but immediately swam upstream again, possibly frightened by the acceleration of the water. During darkness the effectiveness of the by-pass was increased when a submerged spotlight was directed upstream from the center of the by-pass orifice. Large schools of fish congregated in the beam and swam back and forth in the illuminated area with the result that each time a school ventured close to the orifice a few members of the school were caught by the high velocity and drawn into the trap. The majority still retreated upstream, however, just as they had done during daylight.

Many other attempts were made to increase the efficiency of the by-pass. The first change was the addition of a reverse-polarity trap, 3 feet deep and 8 feet

long, the anode row of electrodes being installed at the orifice and the cathode row 2 feet upstream. The electrodes, which consisted of vertical ⅛-inch diameter iron wires spaced 12 inches apart in each row, were energized with 48 volts of direct current. This type of trap had been very successful in attracting fish in the flume experiments in Sweltzer Creek but in the forebay of Baker Dam the fish were repelled by it, probably because they were subjected to a slight electrical shock from stray fields surrounding the electrified zone. As they were unsuccessful the electrodes were removed and an auxiliary entrance was installed to create lower approach velocities upstream from the high velocity at the orifice. This auxiliary entrance consisted of a submerged channel extending 4 feet upstream from the orifice which served to double the effective area of the orifice. When this also was found to be ineffective it was removed and a 20- by 20-foot sheet of heavy canvas was floated on the water surface at the entrance to the by-pass trap to create a protective, shaded area. This was no more successful than the other attempts and was soon removed. Experiments were also conducted to determine

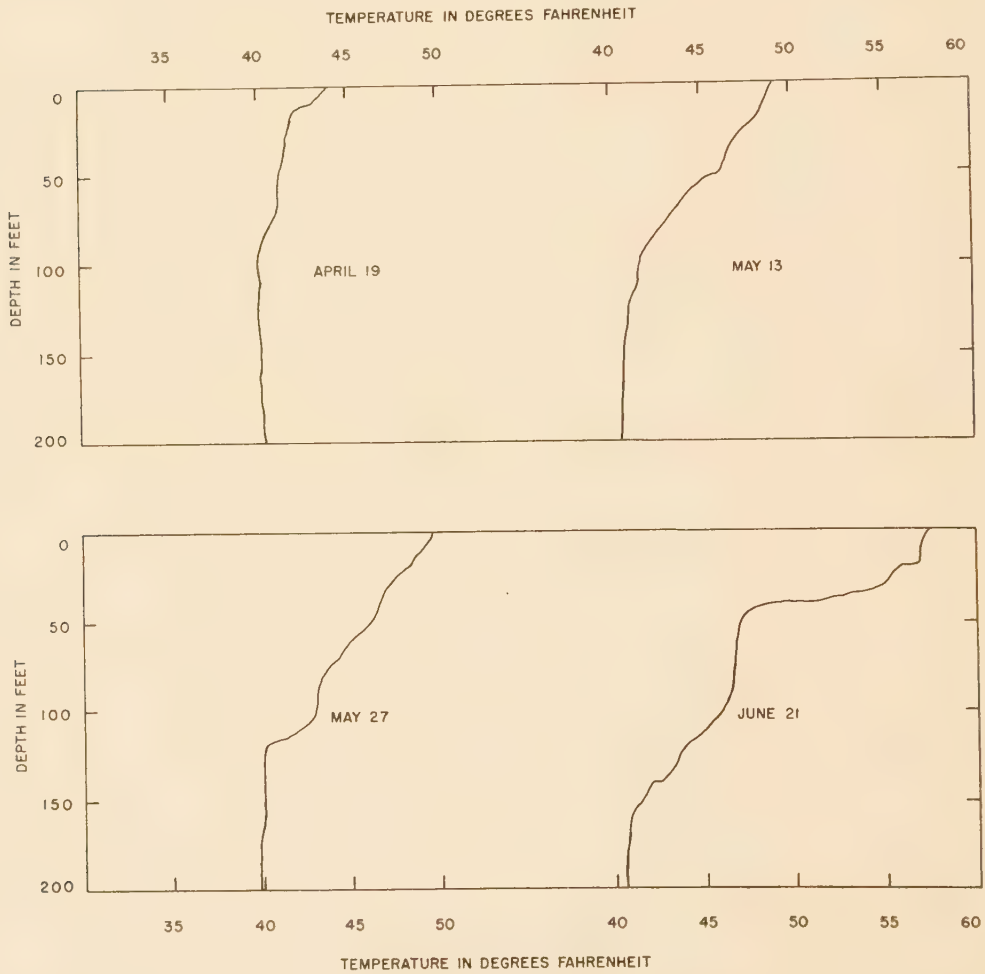


FIGURE 14. Subsurface water temperatures in the forebay of Baker Dam, 1955. (Data from State of Washington Department of Fisheries.)

the effectiveness of increasing the orifice discharge but even when this was almost doubled by operating the by-pass trap as an overflow weir at a head of 1.5 feet, the percentage catch did not increase substantially. Other unsuccessful attempts included painting the upstream side of the trap entrance with black paint and creating a surface current towards the by-pass by means of a pump located about 200 feet upstream.

Another problem was presented by the apparent tendency of the fish to change their normal vertical distribution in the forebay when they encountered the electric screen so that they were guided down to the tunnel intake by the electrified zone. Evidence of this was given by the measured increases in migration rate through the tunnel during periods when the electrodes were energized. The normal vertical distribution was shown by a gill-netting operation that was conducted at the same time as the guiding experiment in the forebay about 500 feet upstream from the dam by the State of Washington Department of Fisheries (Rees, 1955). This investigation revealed that 90 per cent of the coho and 82 per cent of the sockeye were present in the top 15 feet of the forebay and it was found that practically no fish were captured in the gill nets below a depth of 30 feet during the period of the electrical guiding experiment. Observations made by the United States Fish and Wildlife Service with an echo-sounding device ("Sea-scanner") are helpful in interpreting the effect of the electric screen on the vertical distribution of fish in the forebay. An excerpt from the report (Trefethen, 1955) follows:

"An individual school of fingerlings was kept under observation for one hour during one half of which time the electrical array was in operation. The depth of the school was between 20 and 30 feet and generally located within 10 feet of the electrodes.

"During the period when electrical power was supplied to the array, the fingerling school appeared rather dense and it remained consolidated. At times the school moved up to the array and then returned to approximately the original position. The school occasionally moved laterally along the array for about 25 feet.

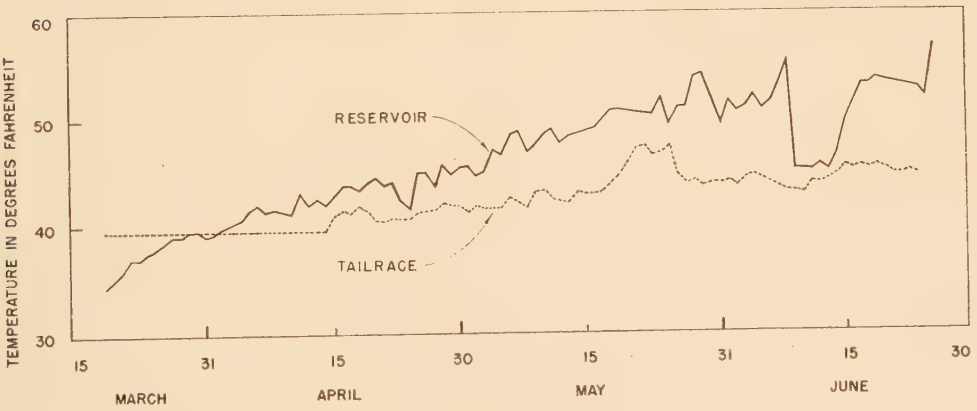


FIGURE 15. Mean daily temperatures of reservoir and tailrace. Reservoir temperature taken three feet below the surface at the trash rack.

"When the electrical power was turned off the fingerlings in the school became slightly scattered. The movements of the school as a unit decreased. The position of the school remained constant within a few feet of the electrical array at a depth of about 25 feet. Other schools migrating downstream appeared to merge with the school under observation. The fingerling school being observed did not appear to enlarge, suggesting that fingerlings were passing through the array when the power was off.

"An interesting result of observations near the electrical array was the presence of fingerling schools at depths greater than 50 feet. Since the electrodes extend vertically into the water for only 50 feet, it appeared that some schools of fingerling pass under the electrodes and the maximum effectiveness was probably not obtained."

Although it is possible that the vertical distribution of migrants may be limited at times by the temperature pattern in the forebay, previous records show that the normal downstream migration occurs before the surface of the reservoir has warmed up sufficiently to produce a subsurface zone of sharp temperature change. The peak of migration in 1955 occurred about May 20 but the thermocline did not form until about June 21. Investigations in 1951 and 1952 (Hamilton and Andrew, 1954) also showed that the thermoclines were not well established until after the peak migrations had occurred, so it is probable that in normal years the fish would not be prevented from increasing their swimming depth, when encountering the electric screen, by a subsurface zone of sharp temperature gradient. In 1955 the tailrace water was a few degrees cooler than that in the surface layers of the forebay but the fish appeared able to make this temperature adjustment very quickly. Subsurface temperatures in the forebay for the period of the experiment in 1955 are given in Figure 14 and the mean daily forebay and tailrace surface temperatures in Figure 15.

A number of less important problems also became apparent during the progress of the experiment. Maintenance of the motor-generator set and other electrical equipment was difficult because the electric screen had to be energized continuously for long periods of time. The accumulation of algae and debris on the electrodes was another hazard. In practice, it would probably be necessary to use rigidly supported electrodes and to provide a method of cleaning and replacing them while they are energized. It would also be necessary to duplicate certain elements of the installation, including the power supply and other electrical equipment.

## DISCUSSION

This study has revealed that the practical guiding effectiveness of artificial stimuli cannot be measured in laboratory or small-scale field experiments and that the problem of guiding fingerling salmon at dams is far from being solved at the present time. Although nearly all the artificial stimuli tested were partially effective in attracting or repelling fish, they maintained a very temporary control over the fish. The tendency of fingerling salmon to follow the main flow of water when they are moving downstream makes the problem of guiding especially difficult. It is necessary that the artificial stimulus used to guide fish be sufficiently intense and of such a nature that it compels the fish to move against their distinct urge to follow the main flow and it must also maintain control of the fish until they have been guided along a path of low flow to a safe by-pass.

In the preliminary experiments conducted in Sweltzer Creek the galvanotropic screen was found to maintain control over the fish much more effectively than sound or than lights, air bubbles and other visual stimuli. It was found that excellent results were obtained with an electric screen energized with direct current or interrupted direct current but that condenser discharge impulses, alternating current and rectified 60-cycle and 400-cycle alternating current were not very effective. The electrode arrangement was also very important; small-diameter electrodes were more effective than large and a spacing of 6 inches or 12 inches between electrodes in each row, with the two rows 2 feet or 4 feet apart was found to be most effective. Efficiencies higher than 90 per cent were achieved in the largest experiments that were possible in the shallow water at this experimental site but when the same type of screen was tried at Baker Dam the results were very disappointing: the fish went under or through the electric screen and were not guided to the by-pass.

The provision of an efficient by-pass appears to be of primary importance to the success of any method of diverting downstream migrants. The by-pass must be easily accessible to the fish after they have been diverted and must be attractive so that the fish will enter it without delay. Since artificial stimuli have not been found that can maintain control over the fish for long periods of time the efficiency of diversion is dependent upon the effectiveness of the by-pass in collecting the fish as well as the effectiveness of the stimulus in deflecting and guiding them. The high guiding efficiencies obtained in the experiments in Sweltzer Creek might be attributed to the relatively large size of the by-pass, which discharged a relatively large proportion of the total stream flow. The difficulty in providing an equally effective by-pass at a large hydroelectric installation is readily apparent because of the greatly increased area and flow to be screened.

Although it is likely that electric screens could be developed for certain specific applications it is apparent that these will be limited. Furthermore, it is very unlikely that electric screens will be 100 per cent effective at large installations as some fish escaped through electrical barriers even in the controlled small-scale experiments where a very effective by-pass was used. Water velocity is another limiting factor in the applicability of electric screens; the swimming ability of the fish is impaired by electrical exposure and the maximum permissible velocity

must therefore be considerably lower than 1.5 feet per second, which has been considered as the maximum permissible velocity for mechanical fish screens. Water resistivity, too, is a limiting factor. A further and very important limitation is that a galvanotropic screen operating with a fixed voltage gradient would be effective for guiding a certain size range of fish but larger fish would be immobilized or killed and smaller fish would be unaffected by the electrical exposure. Chum and pink salmon fingerlings migrating at the same time as the yearling sockeye in Sweltzer Creek exhibited no response to the intensities of electrical stimuli that were effective in guiding sockeye but adult trout, being larger than the sockeye, were severely immobilized. In practice, therefore, there would have to be several separate electric screens energized with different voltages in order to prevent large fish from coming in contact with the high voltage gradients required to deflect the smallest fish. Furthermore, since the investigation at Baker Dam showed that fish tended to sound under the electric screen, it would be necessary to extend the electrodes much deeper, possibly to the bottom of the forebay, or to construct a solid barrier under the electrodes.

The poor results obtained in the experiment at Baker Dam also suggest that the effectiveness of electric screens may decrease when the size of the electric screen is increased. In the small-scale experiments the fish followed along the upstream side of the electric screen to the by-pass but an entirely different result was obtained in the large forebay at Baker Dam. It is possible that in Sweltzer Creek the fish in their passage downstream were accustomed to being confined and therefore were easily guided into the by-pass. In the large forebay at Baker Dam they were less restricted and therefore were perhaps more reluctant to be confined by the electric screen. It is also possible that the fish were weakened as a result of repeated electrical exposure and eventually were unable to swim upstream out of the electrified area.

Another very important consideration regarding the practicability of electric screens is the latent effect that electrical exposure might have on the fish. It has been shown by Nakatani (1955) that physiological changes do occur after such exposure and it is possible therefore that survival and reproductive ability may also be affected. An investigation of the latent effects of electrical exposure was initiated in connection with the guiding experiments at Cultus Lake in 1954 but the complete results will not be available until the fish return as adults in 1956. One of the apparent immediate effects of electrical exposure is that the fish appear to be fatigued and during this condition predation might be a serious factor. Another possible effect is that the normal migration may be hindered or delayed so that a proportion of the fish would be prevented from completing their seaward migration. The possible adverse effects of electrical exposure must be studied thoroughly before electric screens can be considered for practical use.

It is evident that neither electric screens nor other guiding methods have yet been developed to solve the problem of protecting downstream-migrant salmon at large dams.

## CONCLUSIONS

1. No success was achieved in guiding downstream-migrant sockeye and coho salmon in tests of a prototype electric screen at Baker Dam.
2. In small-scale experiments conducted at Cultus Lake a properly designed electric screen was more effective for guiding downstream-migrant sockeye salmon than sound, light, shade, air bubbles and other visual stimuli.
3. The galvanotropic screen, consisting of two closely spaced parallel rows of electrodes energized with a galvanotropic stimulus that oriented the fish and attracted them back upstream, was more effective than electric screens that did not utilize the galvanotropic response.
4. Since artificial stimuli can control the behavior of downstream migrants for only short periods of time, the fish must be guided as quickly as possible to a very efficient by-pass.
5. The guiding methods tested were found to be impractical at the present stage of development for protecting downstream-migrant salmon at large dams because of the many limitations and practical problems involved.

## LITERATURE CITED

Aserinsky, E., G. L. Hoard, R. E. Nakatani and L. A. Verhoeven.
1954. Factors in pulsated direct current which cause electrotaxis and side effects in young salmon. School of Fisheries, University of Washington, Technical Report No. 5, unpublished.

Bramsnaes, F., M. Jul, and C. V. Otterstrøm.
1945. Barriers against fish by means of electricity or veils of air. Report of Danish Biological Station, v. 47.

Brett, J. R., D. MacKinnon and D. F. Alderdice.
1954. Trough experiments on guiding sockeye salmon fingerlings. Progress Reports of the Pacific Coast Stations of the Fisheries Research Board of Canada, No. 99.

Burner, C. J. and H. L. Moore.
1953. Attempts to guide small fish with underwater sound. U. S. Department of the Interior, Fish and Widlife Service, Special Scientific Report: Fisheries No. 111.

Chapman, W. M.
1935. Experiments with revolving fish screens. State of Washington Department of Fisheries, unpublished.

Cooper, A. C.
1952. Downstream-migrant study at Cultus Lake in 1952. International Pacific Salmon Fisheries Commission, unpublished.

Fields, P. E. and G. L. Finger.
1954. The reaction of young salmonidae to light. School of Fisheries, University of Washington, Report No. 2, unpublished.

Fields, P. E., G. L. Finger and L. A. Verhoeven.
1954. The use of a chain barrier to guide young salmon. School of Fisheries, University of Washington, Report No. 1, unpublished.

Fry, D. E.
1950. Moving lights lure fish past diversion channels. Electrical World, v. 133, No. 15.

Groody, T., A. Loukashkin and N. Grant.
1952. A preliminary report on the behavior of the Pacific Sardine *(Sardinops caerulea)* in an electrical field. Proceedings of the California Academy of Sciences, v. XXVII, No. 8.

Hermann, L.
1885. Eine Wirkung galvanische Strome auf Organismen. Pflüg. Arch. ges. Physiol., Bd. 37.

Hamilton, J. A. R. and F. J. Andrew.
1954. An investigation of the effect of Baker Dam on downstream-migrant salmon. International Pacific Salmon Fisheries Commission, Bull. VI.

Holmes, H. B.
1948. History, development and problems of electric fish screen. U.S. Department of the Interior, Fish and Wildlife Service, Special Scientific Report No. 53.

International Pacific Salmon Fisheries Commission.
1955. Annual Report for 1954.

Janssen, J. F.
1938. Air bubbles as a fish scare. California Fish and Game, v. 24, No. 3.

Lethlean, N. G.
1953. An investigation into the design and performance of electric fish screens and an electric fish counter. Transactions of the Royal Society of Edinburgh, v. LXII, Part II, No. 13.

McKernan, D. L.
1940. A progressive report of experiments on the downstream migrating chinook salmon fingerlings at the Dryden ditch screens. State of Washington Department of Fisheries, unpublished.

McMillan, F. O.
1828. Electric fish screen. Bulletin of the U.S. Bureau of Fisheries, v. XLIV.

Morgan, M.E.
1953. The response of a tropical fish to direct current and its application to the problems of electrofishing in sea water. Pacific Science, v. VII, No. 4.

Nakatani, R. E.
1955. Effects of electroshock on some blood constituents of salmon: I. Inorganic phosphate and hematocrit values of the blood of young silver salmon. School of Fisheries, University of Washington, Technical Report No. 15, unpublished.

Nicolai, L.
1930. Über Elektrotaxis und Elektronarkose von Fischen. Pflüg. Arch. ges. Physiol., Bd. 224.

Rayner, H. J.
1949. Direct current as aid to the fishery worker. Progressive Fish Culturist, v. 11, No. 3.

Rees, W. H.
1955. Summary report on the experimental testing of fishing gear for determining the vertical and horizontal distribution of seaward migrants in the forebays of dams. State of Washington Department of Fisheries, unpublished.

Scheminzky, F.
1924. Versuche über Elektrotaxis und Elektronarkose. Pflüg. Arch. ges. Physiol., Bd. 202.

Schoeneman, D. E. and C. O. Junge, Jr.
1954. Investigations of mortalities to downstream migrant salmon at two dams on the Elwha River. State of Washington Department of Fisheries, Research Bull. No. 3.

Smolian, K.
1944. Die Electrofischerei. Samml. Fischer. Zeitfragen der Deut. Fischerei, Heft 35.

Trefethen, P. S.
1955. Observations on the vertical distribution of fingerlings in the forebay of Baker Dam. Pacific Salmon Investigations, United States Fish and Wildlife Service, Technical Progress Report No. 8, unpublished.

Van Harreveld, A.
1938. On galvanotropism and oscillotaxis in fish. Journal of Experimental Biology, v. 15, No. 2.

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